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Invention: PRISM OPTICAL ELEMENT, IMAGE OBSERVATION APPARATUS AND IMAGE DISPLAY APPARATUS

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This is a:

☐ Provisional Application

☐ Regular Utility Application

☒ Continuing Application
  ☒ The contents of the parent are incorporated by reference

☐ PCT National Phase Application

☐ Design Application

☐ Reissue Application

☐ Plant Application

☐ Substitute Specification
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SPECIFICATION

TITLE OF THE INVENTION

PRISM OPTICAL ELEMENT, IMAGE OBSERVATION APPARATUS AND IMAGE DISPLAY APPARATUS

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BACKGROUND OF THE INVENTION

The present invention relates to a prism optical element, an image observation apparatus and an image display apparatus. More particularly, the present invention relates to a head- or face-mounted image display apparatus that can be retained on the observer's head or face.

As an example of conventional head- or face-mounted image display apparatus, an image display apparatus disclosed in Japanese Patent Application Unexamined Publication (KOKAI) No. 3-101709 (1991) is known. In this image display apparatus, an image that is displayed by an image display device is transmitted as an aerial image by a relay optical system including a positive lens, and the aerial image is projected into an observer's eyeball as an enlarged image by an ocular optical system formed from a concave reflecting mirror.

U.S. Patent No. 4,669,810 discloses another type of convention image display apparatus. In this apparatus, an image of a CRT is transmitted through a relay optical system to form an intermediate image, and the image is projected into an observer's eye by a combination of a reflection holographic element and a combiner having a hologram surface.

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U.S. Patent No. 4,026,641 discloses another type of conventional image display apparatus. In the conventional image display apparatus, an image of an image display device is transferred to a curved object surface by an image

5   transfer device, and the image transferred to the object surface is projected in the air by a toric reflecting surface.

U.S. Reissued Patent No. 27,356 discloses another type of conventional image display apparatus. This apparatus is

10   an ocular optical system designed to project an object surface onto an exit pupil by a semi-transparent concave mirror and a semitransparent plane mirror.

Other known image display apparatuses include those which are disclosed in U.S. Patent Nos. 4,322,135 and

15   4,969,724, European Patent No. 0,583,116A2, and Japanese Patent Application Unexamined Publication (KOKAI) No. 7-333551 (1995).

However, an image display apparatus of the type in which an image of an image display device is relayed, as in

20   Japanese Patent Application Unexamined Publication (KOKAI) No. 3-101709 (1991) and U.S. Patent No. 4,669,810, must use several lenses as a relay optical system in addition to an ocular optical system, regardless of the type of ocular optical system. Consequently, the optical path length

25   increases, and the optical system increases in both size and weight.

Because a head-mounted image display apparatus is fitted to the human body, particularly the head, if the amount to

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which the apparatus projects from the user's face is large, the distance from the supporting point on the head to the center of gravity of the apparatus is long. Consequently, the weight of the apparatus is imbalanced when the apparatus

5 is fitted to the observer's head. Further, when the observer moves or turns with the apparatus fitted to his/her head, the apparatus may collide with something. That is, it is important for a head-mounted image display apparatus to be small in size and light in weight. An essential factor

10 in determining the size and weight of the apparatus is the arrangement of the optical system.

However, if an ordinary magnifier alone is used as an ocular optical system, exceedingly large aberrations are produced, and there is no device for correcting them. Even

15 if spherical aberration can be corrected to a certain extent by forming the configuration of the concave surface of the magnifier into an aspherical surface, other aberrations such as coma and field curvature remain. Therefore, if the field angle for observation is increased, the image display

20 apparatus becomes impractical. Alternatively, if a concave mirror alone is used as an ocular optical system, it is necessary to use not only ordinary optical elements (lens and mirror) but also a device for correcting field curvature by an image transfer device (fiber plate) having a surface

25 which is curved in conformity to the field curvature produced.

In an image display apparatus of the type in which an image of an image display device is projected into an

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observer's eyeball by using a toric reflecting surface as in
U.S. Patent No. 4,026,641, field curvature that is produced
by the decentered toric reflecting surface is corrected by
curving the object surface itself. Therefore, it is
5   difficult to use a flat display, e.g. an LCD (Liquid Crystal
Display), as an image display device.

In a coaxial ocular optical system in which an object
surface is projected on an observer's pupil by using a
semitransparent concave mirror and a semitransparent plane
10   mirror as in U.S. Reissued Patent No. 27,356, because two
semitransparent surfaces are used, the brightness of the
image is reduced to as low a level as 1/16, even in the case
of a theoretical value. Further, because field curvature
that is produced by the semitransparent concave mirror is
15   corrected by curving the object surface itself, it is
difficult to use a flat display, e.g. an LCD (Liquid Crystal
Display), as an image display device.

SUMMARY OF THE INVENTION
20   In view of the above-described problems of the
conventional techniques, an object of the present invention
is to provide an extremely compact image observation
apparatus and image display apparatus which are capable of
providing an observation image that is clear and has minimal
25   aberration and minimal distortion even at a wide field
angle, and a prism optical element for use in these
apparatuses.

To attain the above-described object, the present

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invention provides a prism optical element formed from a plurality of surfaces facing each other across a medium having a refractive index (n) larger than 1 (n>1). The prism optical element has a first surface, a second surface,

5 a third surface, and a fourth surface. The first surface has both a transmitting action through which light rays enter the prism optical element or exit therefrom and a reflecting action by which light rays are internally reflected in the prism optical element. The second surface

10 is disposed to face the first surface across the medium and has a reflecting action by which light rays are internally reflected in the prism optical element. The third surface is disposed substantially close to the second surface to face the first surface across the medium and has a

15 reflecting action by which light rays are internally reflected in the prism optical element. The fourth surface has such a transmitting action that when the first surface has an action through which light rays enter the prism optical element, the fourth surface has an action through

20 which light rays exit from the prism optical element, whereas, when the first surface has an action through which light rays exit from the prism optical element, the fourth surface has an action through which light rays enter the prism optical element. The prism optical element satisfies

25 the following condition:

$$\sin^{-1}(1/n_d) \leqq \theta_{r3} \leqq 60^\circ \qquad\qquad ...(1)$$

where n_d is the refractive index for the spectral d-line of the medium, and θ_{r3} is the angle of internal

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reflection of an arbitrary light ray at the third surface.

In the present invention, the arrangement of the second and third surfaces is not necessarily limited to the one in which surfaces designed separately from each other are
5 disposed adjacent to each other, but includes an arrangement in which the second and third surfaces are formed by using one identical surface such that one region of the surface acts as the second surface, and another region of the surface acts as the third surface. In this case, an overlap
10 region that acts as both the second and third surfaces may be present because a bundle of light rays has a width.

One image observation apparatus according to the present invention has an image forming device and an ocular optical system having an action by which an image formed by
15 the image forming device is led to an eyeball of an observer. The ocular optical system includes a prism member having at least three surfaces. The space between the at least three surfaces is filled with a single medium having a refractive index (n) larger than 1 (n>1). The prism member
20 has an action by which light rays emitted from the image forming device are internally reflected at least three times. At least two of the at least three internal reflections are total reflections. At least one of the at least two total reflections is performed by a surface
25 disposed on a side of the single medium that is closer to the observer. The surface is curved so as to correct aberrations produced by the internal reflections in the prism member. At least two of the at least three surfaces

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of the prism member are disposed to face each other such that an external scene can be observed through the at least two surfaces, and that a distortion produced when the external scene is observed through the single medium is

5   minimized.

Another image observation apparatus according to the present invention has an image forming device and an ocular optical system having an action by which an image formed by the image forming device is led to an eyeball of an

10 observer. The ocular optical system includes at least a prism member. The prism member has at least four optical surfaces having a transmitting or reflecting optical action. The space surrounded by the at least four optical surfaces is filled with a single medium having a refractive index (n)

15 larger than 1 (n>1). The at least four optical surfaces include a first surface, a second surface, a third surface, and a fourth surface. The first surface has both a transmitting action and a reflecting action and is disposed on a side of the prism member that is closer to the

20 observer's eyeball. The second surface has a reflecting action and is disposed to face the first surface across the medium. The second surface is at least decentered or tilted with respect to the observer's visual axis. The third surface has a reflecting action and is disposed to face the

25 first surface across the medium at a position substantially adjacent to the second surface. The fourth surface is disposed such that one end thereof is substantially adjacent to the first surface, and the other end thereof is

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substantially close to the third surface. At least the third surface has a totally reflecting action. The first surface, the single medium and the third surface are arranged to have an external scene observation action by which an external scene can be observed through the first surface, the single medium and the third surface.

Still another image observation apparatus according to the present invention has an image forming device and an ocular optical system having an action by which an image formed by the image forming device is led to an eyeball of an observer. The ocular optical system includes at least a prism member. The prism member has at least four optical surfaces having a transmitting or reflecting optical action. The space surrounded by the at least four surfaces is filled with a single medium having a refractive index (n) larger than 1 (n>1). The at least four optical surfaces include a first surface, a second surface, a third surface, and a fourth surface. The first surface has both a transmitting action and a reflecting action and is disposed on a side of the prism member that is closer to the observer's eyeball. The second surface has a reflecting action and is disposed to face the first surface across the medium. The second surface is at least decentered or tilted with respect to the observer's visual axis. The third surface has a reflecting action and is disposed to face the first surface across the medium at a position substantially adjacent to the second surface. The fourth surface is disposed such that one end thereof is substantially adjacent to the first surface, and

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the other end thereof is substantially close to the third

surface. At least the second or third surface has a totally

reflecting action. In addition, a line-of-sight detecting

device for detecting an observer's line of sight is disposed

5   near a totally reflecting region of the second or third

surface that has a totally reflecting action.

An image display apparatus according to the present

invention has an image display device and an ocular optical

system for leading an image formed by the image display

10   device to an eyeball of an observer such that the image can

be observed as a virtual image. The ocular optical system

includes a decentered prism in which a space formed by at

least two surfaces is filled with a medium having a

refractive index larger than 1. The at least two surfaces

15   include a first surface positioned immediately in front of

the observer's eyeball, and a second surface which is a

reflecting surface facing the first surface. At least one

of the at least two surfaces is a curved surface decentered

or tilted with respect to the observer's visual axis. The

20   ocular optical system further includes an aberration

correcting device disposed outside the second surface to

correct aberrations due to decentration produced by the

first and second surfaces with respect to light from an

external scene.

25   Another image display apparatus according to the

present invention has an image display device and an ocular

optical system for leading an image formed by the image

display device to an eyeball of an observer such that the

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image can be observed as a virtual image. The ocular optical system includes a decentered prism in which a space formed by at least three surfaces is filled with a medium having a refractive index larger than 1. The at least three surfaces include a refracting and internally reflecting surface positioned immediately in front of the observer's eyeball; an outside world-side internally reflecting surface disposed on the outside world side of the ocular optical system to face the refracting and internally reflecting surface; and a refracting surface through which a bundle of light rays emitted from the image display device enters the decentered prism. At least one of the at least three surfaces is decentered or tilted with respect to the observer's visual axis. The at least three surfaces are arranged to perform at least three internal reflections. The ocular optical system further includes a second optical element that cancels a power produced by the refracting and internally reflecting surface, which is positioned immediately in front of the observer's eyeball, and the outside world-side internally reflecting surface with respect to external light when an external scene is observed through the two surfaces. The second optical element is disposed on the outside world side of the outside world-side internally reflecting surface.

In the present invention, the arrangement of the second and third surfaces is not necessarily limited to the one in which surfaces designed separately from each other are disposed adjacent to each other, but includes an arrangement

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in which the second and third surfaces are formed by using one identical surface such that one region of the surface acts as the second surface, and another region of the surface acts as the third surface. In this case, an overlap

5   region that acts as both the second and third surfaces may be present because a bundle of light rays has a width.

The arrangements and operations of the prism optical element, image observation apparatus and image display apparatus according to the present invention will be

10   described. In the description of the image observation apparatus and image display apparatus in particular, the explanation will be made on the basis of backward ray tracing in which light rays are traced from the observer's pupil position toward the image display device for the

15   convenience of designing the optical system, unless otherwise specified.

In the image observation apparatus according to the present invention, light rays from the image display device (image forming device) are internally reflected three times

20   in the ocular optical system, thereby enabling the optical path to be folded very effectively, and thus realizing an extremely thin ocular optical system. Two of the three internal reflections are specified as total reflections. Consequently, the area that requires reflection coating is

25   markedly reduced, thereby succeeding in realizing a compact, lightweight and low-cost ocular optical system. By specifying two of the three reflections as total reflections, it is possible to minimize the incidence of a

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ghost image due to the occurrence of unwanted light or the
reduction in contrast caused by flare. Usually, in an
optical system having internal reflection and filled with an
optical medium having a refractive index larger than 1, the
5   influence of unwanted light emerging from an image display
device at a large exit angle and unwanted light due to
reflection in a path other than the proper ray path gives
rise to a problem. In the present invention, the number of
reflection coating surfaces is reduced by using two totally
10   reflecting surfaces. Consequently, unwanted light other
than the desired bundle of light rays emanating from the
image display device and reaching the observer's pupil is
transmitted by the two internally reflecting surfaces.
Thus, unwanted light reaching the observer's pupil is
15   markedly reduced.

The above-described action will be described in detail
with reference to Figs. 20(a) and 20(b). Figs. 20(a) and
20(b) are fragmentary enlarged views showing a part of a
decentered prism 12 through which light from an image
20   display device 7 enters. The decentered prism 12 has
three surfaces 101, 102 and 103 decentered with respect to
the optical axis, and the space formed by the surfaces 101,
102 and 103 is filled with a medium having a refractive
index larger than 1. Reference numeral 15 denotes an
25   observer's eyeball. Reference numeral 101 denotes an
entrance surface. Reference numeral 102 denotes an outside
world-side reflecting or totally reflecting surface.
Reference numeral 103 denotes an observer-side refracting or

reflecting surface. Fig. 20(a) shows an arrangement in
which the reflecting surface 102 is provided with reflection
coating. Fig. 20(b) shows an arrangement in which the
reflecting surface 102 is a totally reflecting surface,

5   which is provided with no reflection coating. In the case
of Fig. 20(a), light emitted from the left-hand end of the
image display device 7 at a large exit angle enters the
decentered prism 12 while being refracted by the entrance
surface 101. The incident light is reflected by the

10   reflecting surface 102, which is provided with reflection
coating. The reflected light passes through the refracting
surface 103 and enters the observer's eyeball 15.
Accordingly, the observer sees an unwanted electronic image
in the upper part of the observer's visual field in addition

15   to the proper image (hereinafter referred to as "electronic
image") of the image display device 7. Alternatively, flare
appears in the upper part of the observer's visual field.

In the case of Fig. 20(b), light emitted from the left-
hand end of the image display device 7 at a large exit angle

20   enters the decentered prism 12 while being refracted by the
entrance surface 101, and is incident on the reflecting
surface 102, which is provided with no reflection coating.
Because the incident angle is smaller than the critical
angle, the unwanted light passes through the reflecting

25   surface 102. Accordingly, the unwanted light is transmitted
to a side of the decentered prism 12 that is remote from the
observer and therefore does not enter the observer's eyeball
15. In other words, neither a ghost image nor flare occurs.

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The above-described action can be similarly caused to take place at any totally reflecting surface in addition to the reflecting surface in this example. That is, the above-described action can be attained by setting the optical system such that a bundle of light rays in the ray path for observation of the proper electronic image has an incident angle not smaller than the critical angle, and that any other ray bundle having an exit angle which may cause ghost or flare has an incident angle smaller than the critical angle at a totally reflecting surface. It becomes easy to obtain the above-described effect by setting two totally reflecting surfaces as described above. Thus, it becomes possible to provide the observer with a clear observation image which is free from a ghost image and which has a minimal reduction in contrast due to flare.

First, assuming that the prism optical element according to the present invention is used as an ocular optical system (observation optical system) of an image observation apparatus or an image display apparatus, the prism optical element is formed from a prism member in which at least three internal reflections take place, and the prism member is filled with a medium having a refractive index larger than 1. Therefore, the ocular optical system can be made extremely thin by the above-described optical path folding effect. In addition, aberration correction can be made even more effectively by the arrangement in which at least three internal reflections take place. Thus, it is possible to present an observation image which is clear as

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far as the edges of the image field. In this regard, the prism optical element according to the present invention will be described below more specifically.

The principal power of the prism optical element is given by the second surface, which is a reflecting surface. In this case, the second surface can be formed with a large radius of curvature in comparison to a refracting system of the same power as that of the reflecting surface. Therefore, aberrations produced by the second surface can be minimized. Further, the outside world-side reflecting surface is divided into two different surfaces (i.e. the second and third surfaces). Therefore, it becomes possible to set the direction of reflected light as desired independently of the curvature of each surface. Accordingly, the optical system can be so shaped as to conform to the curve of the observer's face, and the image display device can be disposed such that the back of the device faces the observer. In particular, when the image display device is an LCD or the like that requires a back light, the back light and the associated electric system are provided on the observer side. Therefore, no part of the image display device projects forwardly, and the amount to which the whole image display apparatus projects from the observer's face can be minimized.

In general, when a concave mirror is decentered or tilted with respect to the optical axis, aberrations due to decentration are produced, which do not occur in a coaxial system. In the case of the prism optical element according

to the present invention also, when it is used in an image observation apparatus or an image display apparatus, aberrations due to decentration are produced because the second surface is decentered or tilted with respect to the observer's visual axis. In particular, astigmatism and coma occur even on the optical axis because there is a difference in power between a direction along a plane containing the optical path of the axial principal ray (i.e. tangential direction) and a direction perpendicular to a plane containing the visual axis and the optical path of the axial principal ray (i.e. sagittal direction). The aberrations due to decentration produced by the second surface can be corrected by forming at least one of the at least four surfaces constituting the prism optical element from a surface having different powers in the tangential and sagittal directions, i.e. a rotationally asymmetric surface.

An even more effective way of correcting the aberrations due to decentration is to use a surface having only one plane of symmetry to form at least one of the surfaces constituting the prism optical element. When the image display device is disposed on the observer's visual axis (i.e. axial principal ray), a bilaterally symmetric observation image can be projected into the observer's eyeball by using a surface having a plane of symmetry in the sagittal direction as at least one of the surfaces constituting the ocular optical system. On the other hand, if the surface is arranged to have no plane of symmetry in the tangential direction, the degree of freedom in the

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tangential direction increases, and it is possible to even more favorably correct decentration aberrations occurring in a plane containing the optical path of the axial principal ray.

5   When the above-described ocular optical system comprises at least four surfaces, reflection taking place at the first surface may be total reflection. If the first surface, which is a surface disposed immediately in front of the observer's pupil, is a totally reflecting surface, a

10   region through which light rays exit from the ocular optical system and an internally reflecting region can be arranged to overlap each other. In other words, a single surface can be arranged to perform both transmitting and reflecting actions. Accordingly, it is possible to construct a compact

15   ocular optical system.

In addition, it is possible to provide a clearer observation image because the above-described ghost and flare reducing effect by the totally reflecting surface can also be obtained at the first surface. Further, because

20   only the second surface requires reflection coating, the productivity improves, and a lower-cost image display apparatus can be realized.

In the above-described prism optical element, it is desirable to satisfy the following condition:

25     $$\sin^{-1}(1/n_d) \leqq \theta_{r3} \leqq 60^\circ \qquad\qquad ...(1)$$

where n_d is the refractive index for the spectral d-line of the medium, and θ_{r3} is the angle of internal reflection of an arbitrary light ray at the third surface.

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It is important to satisfy the condition (1). By
setting θ_{r3} equal to or greater than $\sin^{-1}(1/n_d)$, the angle
of internal reflection at the third surface becomes equal to
or greater than the critical angle. Consequently, it is
5   possible for an arbitrary light ray emitted from the image
display device to be totally reflected at the third surface.

If the angle of reflection at the third surface is
excessively large, the prism optical element becomes
undesirably long in the direction (tangential direction)
10   perpendicular to the visual axis. In the case of a wide-
field image display apparatus in particular, extra-axial
rays diverge to such an extent that the rays cannot reach
the first surface, which is the subsequent reflecting
surface. Consequently, it becomes impossible to realize the
15   desired image display apparatus. Accordingly, it is
desirable that at the third surface the angle of internal
reflection of an arbitrary light ray emitted from the image
display device should be set not larger than the upper limit
of the condition (1), i.e. 60°.

20   It is more desirable to satisfy the following
condition:

$$\sin^{-1}(1/n_d) \leqq \theta_{r3} \leqq 50^\circ \qquad\qquad ...(2)$$

Because the third surface is a curved surface tilted or
decentered with respect to the optical axis (axial principal
25   ray), the angle of reflection at this surface should be as
small as possible. The smaller the reflection angle, the
smaller the amount of aberration caused by decentration,
particularly comatic aberration due to decentration.

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Accordingly, it is desirable that at the third surface the angle of internal reflection of an arbitrary light ray emitted from the image display device should be set not greater than the upper limit of the condition (2), i.e. 50°.

5   It is important from the viewpoint of realizing a low-cost image display apparatus to use a plane surface as at least one of the surfaces constituting the prism optical element. By doing so, another surface can be defined on the basis of the at least one plane surface. Therefore, it is

10   possible to facilitate the mechanical design and production of an optical system. Consequently, it is possible to shorten the machining or processing time and to facilitate the layout of the whole apparatus. Thus, it is possible to realize substantial reductions in manufacturing costs.

15   Similar advantageous effects can be obtained by using a spherical surface as at least one of the surfaces constituting the prism optical element. In this case, another surface can be readily defined on the basis of the at least one spherical surface. Therefore, the layout of

20   the whole apparatus is also facilitated. Thus, it is possible to realize substantial reductions in manufacturing costs.

It is desirable that the refractive index n of the medium constituting the prism optical element should be

25   larger than 1.3.

It will be clear from the foregoing description that an observation optical apparatus can be constructed by disposing the above-described prism optical element in an

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observation optical system.

In this case, the prism optical element may be disposed in an objective lens. Alternatively, the prism optical element may be disposed in an image erecting device which is disposed behind an objective lens to erect an object image formed by the objective lens. In the latter arrangement, the prism optical element can be arranged to have both an image erecting action and an ocular lens action.

The prism optical element according to the present invention can be used to construct a head-mounted image display apparatus having an image forming device consisting essentially of an LCD (Liquid Crystal Display) or a CRT disposed to face the fourth surface of the prism optical element, or an image forming device consisting essentially of an LCD, a CRT or the like which is relayed by a relay optical system. The head-mounted image display apparatus further has a retaining member adapted to retain both the prism optical element and the image forming device on the observer's face. A bundle of light rays emitted from the image forming device enters the prism optical element through the fourth surface and passes sequentially along the optical path in the prism optical element. More specifically, the incident ray bundle is reflected successively by the third surface, the first surface and the second surface and exits from the prism optical element through the first surface.

In the present invention, the second and third surfaces may be formed from a single identical surface. In this

case, the number of physical surfaces can be reduced by one, and it is therefore possible to simplify the process in terms of the optical design and the production of prism and hence possible to contribute to the achievement of an

5   increase in mass-productivity and reductions in costs. It is desirable that a physically single surface should be arranged to have both the functions of the second and third surfaces, and that internally reflecting regions should overlap each other. By doing so, it is possible to realize

10   a reduction in the size of the prism member.

One image observation apparatus according to the present invention has an image forming device and an ocular optical system having an action by which an image formed by the image forming device is led to an eyeball of an

15   observer. The ocular optical system includes a prism member having at least three surfaces. The space between the at least three surfaces is filled with a single medium having a refractive index (n) larger than 1 (n>1). The prism member has an action by which light rays emitted from the image

20   forming device are internally reflected at least three times. At least two of the at least three internal reflections are total reflections. At least one of the at least two total reflections is performed by a surface disposed on a side of the single medium that is closer to

25   the observer. The surface is curved so as to correct aberrations produced by the internal reflections in the prism member. At least two of the at least three surfaces of the prism member are disposed to face each other such

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that an external scene can be observed through the at least two surfaces, and that a distortion produced when the external scene is observed through the single medium is minimized.

5   In the image observation apparatus according to the present invention, the third surface 5 is a totally reflecting surface, which is provided with no reflection coating. Therefore, external light passing through the third surface 5 and the first surface 3 reaches the

10   observer's eyeball 15. Accordingly, it is possible to observe an external scene in a range α different from an electronic image observation range β. The fact that the observer can observe an external scene image and an electronic image in different partial regions of the visual

15   field means that the observer can simultaneously observe the external scene in the upper region of the observer's visual field and the electronic image in the lower region of the visual field, by way of example. It should, however, be noted that the partial regions of the visual field for

20   observation of different images may be divided in any direction and in any form, e.g. upper and lower regions, or left and right regions, as long as the observer can observe the different images in the respective partial regions. This function enables the observer to recognize the outside

25   world with the image observation apparatus mounted on his or her head or face. Thus, it is possible to provide a safe image observation apparatus that enables the observer to avoid a dangerous situation and to cope with an emergency

situation. Consequently, the range of applications of the
image observation apparatus widens.

In this image observation apparatus, it is desirable
that the image forming device should be an image display
5   device, e.g. an LCD or a CRT disposed such that the image
forming surface thereof faces the fourth surface (it should
be noted that an image display device which is relayed by a
relay optical system is not expected as the image forming
device in the image observation apparatus), and that the
10   second surface should be formed from a curved surface.

The above-described image observation apparatus can be
constructed as a head-mounted image display apparatus by
providing a retaining member that retains both the image
display device and the ocular optical system in front of an
15   observer's eyeball, and arranging the prism member such that
a bundle of light rays emitted from the image display device
enters the prism member through the fourth surface, and the
incident ray bundle is reflected successively by the third
surface, the first surface and the second surface so as to
20   exit from the first surface.

In the above-described image observation apparatus, the
prism member may be fixed at the same position regardless of
whether the observer views the image formed by the image
forming device or an image of an external scene. In this
25   case, it is desirable that the image from the image forming
device and the external-scene image should be capable of
being observed in the respective partial regions through the
first and third surfaces, as described later with reference

to Fig. 7.

The prism member may be provided with a switching device that moves the prism member so as to enable observation modes to change between the observation of the image formed by the image forming device and the observation of the external-scene image.

More specifically, if the prism member is moved such that the first surface of the ocular optical system, which is disposed immediately in front of the observer's eyeball, and the third surface, which is disposed on the outside world side of the ocular optical system to totally reflect a part of the principal rays, lie in the vicinity of the observer's visual axis, the observer can view an external-scene image around the observer's visual axis lying when he or she looks straight ahead, i.e. in the vicinity of the center of the visual field. Therefore, the observer can confirm the external scene in front of his/her eye with the image display apparatus mounted on his/her head or face. Accordingly, it is possible to realize an image display apparatus ensured safety.

If the electronic image is kept displayed, the external scene can be confirmed by moving and returning the ocular optical system to thereby switch the external-scene image and the electronic image from each other. Accordingly, the range of applications widens.

In this case, it is desirable for the switching device to move the prism member such that an optical path extending from the prism member to the observer's eyeball to observe

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the image formed by the image forming device is approximately coincident with an optical path extending from the prism member to the observer's eyeball to observe the external-scene image.

5   If the prism member is adapted to move along a plane containing the optical path of the axial principal ray, the movement of the prism member is rectilinear. Therefore, the arrangement of the moving mechanism is simplified, and the layout of the whole apparatus is facilitated. Consequently,

10   a low-cost image display apparatus can be realized.

If the prism member is movable in a direction perpendicular to the visual axis, the layout of the whole apparatus is facilitated, and the arrangement of the moving mechanism is simplified. Moreover, because there is no

15   change in the amount to which the ocular optical system projects forward from the observer's face even after the movement of the ocular optical system, a small-sized and compact image display apparatus can be provided.

If the prism member is rotatable, it is possible to

20   observe the external scene by moving the prism member through a simple rotating mechanism. Therefore, the mechanism itself becomes less costly. Moreover, if the prism members for the left and right eyes are simultaneously rotated, the external scene can be confirmed with both eyes.

25   Accordingly, the safety is enhanced, and the layout of the apparatus can be simplified.

Another image observation apparatus according to the present invention has an image forming device and an ocular

optical system having an action by which an image formed by
the image forming device is led to an eyeball of an
observer. The ocular optical system includes at least a
prism member. The prism member has at least four optical
5   surfaces having a transmitting or reflecting optical action.
The space surrounded by the at least four optical surfaces
is filled with a single medium having a refractive index (n)
larger than 1 (n>1). The at least four optical surfaces
include a first surface, a second surface, a third surface,
10   and a fourth surface. The first surface has both a
transmitting action and a reflecting action and is disposed
on a side of the prism member that is closer to the
observer's eyeball. The second surface has a reflecting
action and is disposed to face the first surface across the
15   medium. The second surface is at least decentered or tilted
with respect to the observer's visual axis. The third
surface has a reflecting action and is disposed to face the
first surface across the medium at a position substantially
adjacent to the second surface. The fourth surface is
20   disposed such that one end thereof is substantially adjacent
to the first surface, and the other end thereof is
substantially close to the third surface. At least the
third surface has a totally reflecting action. The first
surface, the single medium and the third surface are
25   arranged to have an external scene observation action by
which an external scene can be observed through the first
surface, the single medium and the third surface. It should
be noted that the term "a surface other than the four

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optical surfaces" as used in this description means a prism side surface or a cut surface which has no optical action.

These image observation apparatuses are arranged such that an external scene can be observed through the surface disposed immediately in front of the observer's eyeball and the surface disposed on the outside world side of the ocular optical system. The action and effect of this arrangement will be described below with reference to Fig. 7. Fig. 7 is a sectional view of a decentered prism 12 in which a space formed by four surfaces 3, 4, 5 and 6 which are decentered with respect to an optical axis is filled with a medium having a refractive index larger than 1. In the figure, reference numeral 1 denotes an observer's pupil; 2 denotes an observer's visual axis; 3 denotes a first surface of the decentered prism 12; 4 denotes a second surface of the decentered prism 12; 5 denotes a third surface of the decentered prism 12; 6 denotes a fourth surface of the decentered prism 12; 7 denotes an image display device; 15 denotes an observer's eyeball; and 16 denotes an optical filter. In the actual path of light rays from the image display device 7, light rays emitted from the image display device 7 enter the decentered prism 12 through the fourth surface 6 and are totally reflected by the third surface 5. The reflected light rays are totally reflected by the first surface 3 and then reflected by the second surface 4. Then, the reflected light rays pass through the first surface 3 to project the image of the image display device 7 into the observer's eyeball 15 with the observer's pupil 1 as an exit

pupil.

In the image observation apparatuses according to the present invention, the third surface 5 is a totally reflecting surface, which is provided with no reflection coating. Therefore, external light passing through the third surface 5 and the first surface 3 reaches the observer's eyeball 15. Accordingly, an external scene can be observed in a range α different from an electronic image observation range β. The fact that the observer can observe an external scene image and an electronic image in different partial regions of the visual field means that the observer can simultaneously observe the external scene in the upper region of the observer's visual field and the electronic image in the lower region of the visual field, by way of example. It should, however, be noted that the partial regions of the visual field for observation of different images may be divided in any direction and in any form, e.g. upper and lower regions, or left and right regions, as long as the observer can observe the different images in the respective partial regions. This function enables the observer to recognize the external scene with the image observation apparatus mounted on his or her head or face. Thus, it is possible to provide a safe image observation apparatus that enables the observer to avoid a dangerous situation and to cope with an emergency situation. Consequently, the range of applications of the image observation apparatus widens.

In this image observation apparatus, it is desirable

that the image forming device should be an image display
device, e.g. an LCD or a CRT disposed such that the image
forming surface thereof faces the fourth surface (it should
be noted that an image display device which is relayed by a

5   relay optical system is not expected as the image forming
device in the image observation apparatus), and that the
second surface should be formed from a curved surface.

The above-described image observation apparatus can be
constructed as a head-mounted image display apparatus by

10   providing a retaining member that retains both the image
display device and the ocular optical system in front of an
observer's eyeball, and arranging the prism member such that
a bundle of light rays emitted from the image display device
enters the prism member through the fourth surface, and the

15   incident ray bundle is reflected successively by the third
surface, the first surface and the second surface so as to
exit from the first surface.

In the above-described image observation apparatus, it
is desirable to arrange the surface disposed immediately in

20   front of the observer's eyeball and the surface disposed on
the outside world side of the ocular optical system such
that the composite power of the two surfaces for external
light at respective arbitrary positions thereof is
approximately zero. If the composite power for external

25   light is approximately zero, conditions under which an image
of an external scene is observed become approximately equal
to those for observation with the naked eye, and the
external scene can be observed even more naturally.

Accordingly, when a dangerous or emergency situation occurs, the external scene can be accurately recognized. Consequently, a remarkably safe image display apparatus can be provided.

5   In this case, the first and third surfaces may be formed from curved, spherical or plane surfaces. When the observer views the external scene, light rays from the external scene pass through the totally reflecting region of the internally reflecting surface disposed on the outside

10   world side of the ocular optical system and further through the refracting surface disposed immediately in front of the observer's eyeball and are projected into the observer's pupil. If the two surfaces are not aspherical surfaces but spherical surfaces, an even more natural external-scene

15   image can be readily observed at an off-axis position because there is no change in the curvature of each surface. If the first surface, which is disposed immediately in front of the observer's eyeball, and the third surface, which is disposed on the outside world side of the ocular optical

20   system, are plane surfaces, a natural external-scene image can be observed because each surface has no power. In a case where the two surfaces are perpendicular to the observer's visual axis and parallel to each other, the external scene is observed through merely transparent

25   plates. Accordingly, it is possible to observe an extremely natural external-scene image.

Assuming that ϕ_{t1} denotes the composite power for external light at respective arbitrary regions of the

surface disposed immediately in front of the observer's
eyeball and the surface disposed on the outside world side
of the ocular optical system, it is desirable to satisfy the
following condition:

5           $-0.5 \leq \phi_{t1} \leq 0.5$ (1/millimeter)   ...(3)

where ϕ_{t1} corresponds to each of the power ϕ_{t1} (yz) in
a plane containing the axial principal ray and the power ϕ_{t1}
(xz) in a plane perpendicular to the plane containing the
axial principal ray.

10   By satisfying the condition (3), the magnification for
external light passing through the decentered prism can be
set in the neighborhood of 1. Therefore, it is possible to
observe an even more natural external-scene image.

In the above-described image observation apparatus, the
15   prism member may be fixed at the same position regardless of
whether the observer views an image formed by the image
forming device or an external-scene image. In this case, it
is desirable that the image from the image forming device
and the external-scene image should be capable of being
20   observed in the respective partial regions through the first
and third surfaces, as stated above with reference to
Fig. 7.

The prism member may be provided with a switching
device that moves the prism member so as to enable
25   observation modes to change between the observation of the
image formed by the image forming device and the observation
of the external-scene image.

More specifically, if the prism member is moved such

that the first surface of the ocular optical system, which
is disposed immediately in front of the observer's eyeball,
and the third surface, which is disposed on the outside
world side of the ocular optical system to totally reflect a
part of the principal rays, lie in the vicinity of the
observer's visual axis, the observer can view an external-
scene image around the observer's visual axis lying when he
or she looks straight ahead, i.e. in the vicinity of the
center of the visual field. Therefore, the observer can
confirm the external scene in front of his/her eye with the
image display apparatus mounted on his/her head or face.
Accordingly, it is possible to realize an image display
apparatus ensured safety.

If the electronic image is kept displayed, the external
scene can be confirmed by moving and returning the ocular
optical system to thereby switch the external-scene image
and the electronic image from each other. Accordingly, the
range of applications widens.

In this case, it is desirable to arrange the surface
disposed immediately in front of the observer's eyeball and
the surface disposed on the outside world side of the ocular
optical system such that the composite power of the two
surfaces for external light at respective arbitrary
positions thereof is approximately zero. If the composite
power for external light is approximately zero, the external
scene can be observed even more naturally. Accordingly, it
is possible to avoid a dangerous situation and to cope
appropriately with an emergency situation. Consequently, a

remarkably safe image display apparatus can be provided.

Assuming that ϕ_{t2} denotes the composite power for external light at respective arbitrary positions of the surface disposed immediately in front of the observer's eyeball and the surface disposed on the outside world side of the ocular optical system, it is desirable to satisfy the following condition:

$$-0.5 \leq \phi_{t2} \leq 0.5 \quad \text{(1/millimeter)} \qquad \ldots (4)$$

where ϕ_{t2} corresponds to each of the power ϕ_{t2} (yz) in a plane containing the axial principal ray and the power ϕ_{t2} (xz) in a plane perpendicular to the plane containing the axial principal ray.

By satisfying the condition (4), the magnification for external light passing through the decentered prism can be set in the neighborhood of 1. Therefore, it is possible to observe an even more natural external-scene image.

In this case, it is desirable for the switching device to move the prism member such that an optical path formed from the prism member to the observer's eyeball to observe an image formed by the image forming device is approximately coincident with an optical path formed from the prism member to the observer's eyeball to observe an external-scene image.

If the prism member is adapted to move along a plane containing the optical path of the axial principal ray, the movement of the prism member is rectilinear. Therefore, the arrangement of the moving mechanism is simplified, and the layout of the whole apparatus is facilitated. Consequently, a low-cost image display apparatus can be realized.

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If the prism member is movable in a direction perpendicular to the visual axis, the layout of the whole apparatus is facilitated, and the arrangement of the moving mechanism is simplified. Moreover, because there is no

5 change in the amount to which the ocular optical system projects forward from the observer's face even after the movement of the ocular optical system, a small-sized and compact image display apparatus can be provided.

If the prism member is rotatable, it is possible to

10 observe the external scene by moving the prism member through a simple rotating mechanism. Therefore, the mechanism itself becomes less costly. Moreover, if the prism members for the left and right eyes are simultaneously rotated, the external scene can be confirmed with both eyes.

15 Accordingly, the safety is enhanced, and the layout of the apparatus can be simplified.

Still another image observation apparatus according to the present invention has an image forming device and an ocular optical system having an action by which an image

20 formed by the image forming device is led to an eyeball of an observer. The ocular optical system includes at least a prism member. The prism member has at least four optical surfaces having a transmitting or reflecting optical action. The space surrounded by the at least four surfaces is filled

25 with a single medium having a refractive index (n) larger than 1 (n>1). The at least four optical surfaces include a first surface, a second surface, a third surface, and a fourth surface. The first surface has both a transmitting

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action and a reflecting action and is disposed on a side of the prism member that is closer to the observer's eyeball. The second surface has a reflecting action and is disposed to face the first surface across the medium. The second

5   surface is at least decentered or tilted with respect to the observer's visual axis. The third surface has a reflecting action and is disposed to face the first surface across the medium at a position substantially adjacent to the second surface. The fourth surface is disposed such that one end

10   thereof is substantially adjacent to the first surface, and the other end thereof is substantially close to the third surface. At least second or third surface has a totally reflecting action. In addition, a line-of-sight detecting device for detecting an observer's line of sight is disposed

15   near a totally reflecting region of the second or third surface that has a totally reflecting action. In this case also, the term "a surface other than the four optical surfaces" means a prism side surface or a cut surface which has no optical action.

20   The action and effect of the image observation apparatus when constructed as an image display apparatus will be described below. Disposing the line-of-sight detecting device near the optical system makes it possible to detect the observer's line of sight. Detection of the

25   observer's line of sight will be described below with reference to Figs. 5(a), 5(b) and 6. Fig. 5(a) is a sectional view of an image display apparatus comprising an image display device 7 and a decentered prism 12 in which

a space formed by three surfaces 3, 4 and 6 decentered with respect to an optical axis is filled with a medium having a refractive index larger than 1. Fig. 5(b) is a sectional view of an image display apparatus comprising an

5　image display device 7 and a decentered prism 12 in which a space formed by four surfaces 3, 4, 5 and 6 decentered with respect to an optical axis is filled with a medium having a refractive index larger than 1. Fig. 6 is a sectional view of another image display apparatus comprising

10　an image display device 7 and a decentered prism 12 in which a space formed by four surfaces 3, 4, 5 and 6 decentered with respect to an optical axis is filled with a medium having a refractive index larger than 1. In these figures, reference numeral 1 denotes an observer's pupil; 2 denotes

15　an observer's visual axis; 3 denotes a first surface of an ocular optical system 12; 4 denotes a second surface of the ocular optical system 12; 5 denotes a third surface of the ocular optical system 12; 6 denotes a fourth surface of the ocular optical system 12; 7 denotes an image display device;

20　9 denotes a line-of-sight detecting optical system; 10 denotes a line-of-sight detector; 11 denotes an illuminating device; 12 denotes an ocular optical system; and 15 denotes an observer's eyeball.

In the arrangement shown in Fig. 5(a), a line-of-sight

25　detecting device comprising the line-of-sight detecting optical system 9 and the line-of-sight detector 10 is disposed on the outside world side of a decentered prism constituting the ocular optical system 12 so as to face the

observer's eyeball 15 across the decentered prism. In this case, the image of the observer's pupil 1 needs to pass through the first surface 3, which is disposed immediately in front of the observer's pupil 1, and the second surface

5   4, which is a reflecting surface disposed on the outside world side of the ocular optical system 12, to enter the line-of-sight detecting device (9 and 10). However, the second surface 4, which is disposed on the outside world side of the ocular optical system 12, is a reflecting

10   surface and hence provided with reflection coating. Accordingly, it is necessary in order to lead the image of the observer's pupil 1 to the line-of-sight detecting device (9 and 10) to provide the reflecting surface with a non-coated portion NC (i.e. a hole in the reflection coating).

15   Such a non-coated portion NC would have an adverse effect on the image to be observed.

Figs. 5(b) and 6 show image display apparatuses according to the present invention. The third surface 5, which is a reflecting surface disposed on the outside world

20   side of the ocular optical system 12, is provided such that a part of the third surface 5 totally reflects light incident thereon. The totally reflecting portion of the third surface 5 can reflect light from the image display device 7 without the need of reflection coating. Accordingly, it is

25   unnecessary to provide reflection coating. Thus, the image of the observer's pupil 1 passes through the first surface 3, which is disposed immediately in front of the observer's pupil 1, and further through the totally reflecting portion

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of the third surface 5, which is disposed on the outside world side of the ocular optical system, and it can be detected by the line-of-sight detecting device (9 and 10). Therefore, the observer's line of sight can be detected

5 without the need for providing the reflecting surface of the ocular optical system 12 with a coating hole, which has an adverse effect on the observation of the electronic image.

In this case, it is desirable for the first surface of the decentered prism to have a totally reflecting action.

10 In such a case, it is desirable that the line-of-sight detecting device should be disposed at a position where it detects the observer's line of sight through the totally reflecting region of the second or third surface.

It is desirable for the image display apparatus to have

15 an illuminating device that illuminates the observer's eyeball. By illuminating the observer's eyeball, the image display apparatus can detect a bright image, and it is therefore possible to accurately detect the observer's line of sight. It is desirable that the illuminating device

20 should be provided on the outside world side of the ocular optical system. If an illuminating device 11 is disposed between the observer's face and the ocular optical system 12 as shown in Fig. 5(a), the illuminating device 11 is likely to interfere with the observer's glasses or other thing.

25 However, if the illuminating device 11 is disposed on the outside world side of the ocular optical system 12, it is possible to avoid an interference between the illuminating device 11 and the observer's face. If the illuminating

device 11 is provided such that illuminating light from the illuminating device 11 passes through the totally reflecting portion of the reflecting surface of the ocular optical system 12, the observer's pupil can be illuminated without

5   providing a coating hole.

It is desirable to use an illuminating device employing infrared light. Observation of the electronic image means that the observer's pupil is illuminated by light from the image display device. In the case of a line-of-sight

10 detecting device that needs an image analysis by capturing a feeble virtual image, e.g. cornea reflection method, it is necessary to eliminate a reflection image formed by a bundle of light rays from the image display device, the illumination light quantity of which varies every moment.

15 Usually, the image display device is an LCD or the like, which emits light in the visible wavelength region. Accordingly, the use of infrared light as light emitted from the illuminating device makes it possible to reduce the influence of light from the image display device.

20 In this case also, the image observation apparatus can be constructed as a head-mounted image display apparatus by providing a retaining member that retains the ocular optical system, the image forming device and the line-of-sight detecting device in front of an observer's face.

25 The above-described image observation apparatus may have a device for positioning the image forming device and the ocular optical system with respect to the observer's head.

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Further, it is possible to observe a stereoscopic image with both eyes by providing a device for supporting at least a pair of such image observation apparatuses at a predetermined spacing.

5   Next, an image display apparatus according to the present invention has an image display device and an ocular optical system for leading an image formed by the image display device to an eyeball of an observer such that the image can be observed as a virtual image. The ocular

10   optical system includes a decentered prism in which a space formed by at least two surfaces is filled with a medium having a refractive index larger than 1. The at least two surfaces include a first surface positioned immediately in front of the observer's eyeball, and a second surface which

15   is a reflecting surface facing the first surface. At least one of the at least two surfaces is a curved surface decentered or tilted with respect to the observer's visual axis. The ocular optical system further includes an aberration correcting device disposed outside the second

20   surface to correct aberrations due to decentration produced by the first and second surfaces with respect to light from an external scene.

In this image display apparatus, when an image of an external scene is observed through the first surface, which

25   is positioned immediately in front of the observer's eyeball, and the second surface, which is a reflecting surface disposed to face the first surface, the external-scene image is observed in the same way as in the case of

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observing it through a lens having power asymmetric with respect to the optical axis because at least one of the first and second surfaces is decentered or tilted with respect to the observer's visual axis. Therefore, if an aberration correcting device, e.g. a Fresnel lens, which is arranged to cancel the eccentric power, is disposed on the outside world side of the second surface, it becomes possible for the observer to view an even more natural external-scene image. Further, because a Fresnel lens is an extremely thin optical element, it is possible to provide a compact image display apparatus without causing an increase in the size of the apparatus.

According to the present invention, the Fresnel lens may be replaced by another optical element, e.g. a diffractive optical element or a holographic optical element, provided that the above-described effect can be obtained.

When a Fresnel lens is used, it is desirable that the center of the annular zone of the Fresnel lens should lie in a plane containing the optical path of the axial principal ray from the image display device, and that the Fresnel lens should be decentered perpendicularly to the visual axis in the plane containing the optical path of the axial principal ray. If the Fresnel lens has an axially symmetric configuration, the apparatus becomes excellent in productivity, and the production cost can be reduced. If a Fresnel lens having an axially symmetric power is disposed in the plane containing the optical path of the axial

principal ray in such a manner as to be decentered with
respect to the visual axis, aberrations due to decentration
which are produced by the first and second surfaces with
respect to external light can be corrected even more
5   favorably.

The Fresnel lens may be disposed such that the center
of the annular zone of the Fresnel lens should lie in the
plane containing the optical path of the axial principal
ray, and that the Fresnel lens should be tilted with respect
10   to the visual axial so as to extend along the surface
configuration of the second surface. When disposed to
extend along the surface configuration of the second
surface, the Fresnel lens is tilted with respect to the
observer's visual axis. Accordingly, it is possible to set
15   a power asymmetric with respect to the optical axis and
hence possible to correct even more favorably aberrations
due to decentration which are produced by the first and
second surfaces with respect to external light. Moreover,
the amount to which the apparatus projects from the
20   observer's face reduces, and the space between the ocular
optical system and the Fresnel lens also reduces.
Accordingly, it is possible to provide a remarkably compact
image display apparatus having no useless space.

Another image display apparatus according to the
25   present invention has an image display device and an ocular
optical system for leading an image formed by the image
display device to an eyeball of an observer such that the
image can be observed as a virtual image. The ocular

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optical system includes a decentered prism in which a space formed by at least three surfaces is filled with a medium having a refractive index larger than 1. The at least three surfaces include a refracting and internally reflecting

5   surface positioned immediately in front of the observer's eyeball; an outside world-side internally reflecting surface disposed on the outside world side of the ocular optical system to face the refracting and internally reflecting surface; and a refracting surface through which a bundle of

10   light rays emitted from the image display device enters the decentered prism. The at least three surfaces are arranged to perform at least three internal reflections. The ocular optical system further includes a second optical element that cancels the power produced by the refracting and

15   internally reflecting surface, which is positioned immediately in front of the observer's eyeball, and the outside world-side internally reflecting surface with respect to external light when an external scene is observed through the two surfaces. The second optical element is

20   disposed on the outside world side of the outside world-side internally reflecting surface.

When an image of an external scene is observed through the first surface, which is positioned immediately in front of the observer's eyeball, and the second surface, which is

25   a reflecting surface disposed to face the first surface, the external-scene image is observed in the same way as in the case of observing it through a lens having an eccentric power different for each image height because at least one

of the first and second surfaces is decentered or tilted with respect to the observer's visual axis. Therefore, if the second optical element, which is adapted to cancel the eccentric power produced by the two surfaces with respect to

5   external light, is disposed on the outside world side of the ocular optical system, it becomes possible for the observer to view an even more natural external-scene image in a wide range. Accordingly, it is possible to provide a safe image display apparatus which enables the observer to avoid a

10   dangerous situation and to cope with an emergency situation.

In this case, the ocular optical system may be formed from a decentered prism in which a space formed by four surfaces is filled with a medium having a refractive index larger than 1. The four surfaces include a first surface

15   positioned on the observer's eyeball side and serving as both refracting and reflecting surfaces; a second surface which is a reflecting surface disposed to face the first surface; a third surface which is a reflecting surface disposed to face the first surface at a position adjacent to

20   the second surface; and a fourth surface which is a refracting surface closest to the image display device. At least one of the four surfaces is decentered or tilted with respect to the observer's visual axis. In a case where the ocular optical system comprises four surfaces as described

25   above, the external scene is recognized by external light passing through the first and second surfaces. In this case, it is possible to realize an added function without increasing the overall size of the ocular optical system by

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disposing the second optical element adapted to cancel the eccentric power only at a region covering the second surface.

It is desirable to dispose at least one second optical
5   element on the outside world side of the second or third surface so that the external scene can be observed through the first surface, the second surface and the second optical element or through the first surface, the third surface and the second optical element. If the second optical element
10   having the action of canceling the eccentric power is provided on the outside world side of the second surface, a natural external-scene image can be observed in approximately the same region as the region for observation of the electronic image. If the second optical having the
15   action of canceling the eccentric power is provided on the outside world side of the third surface, a natural external-scene image can be observed in a region different from the region for observation of the electronic image. If two second optical elements are disposed on the outside world
20   sides of the second and third surfaces, respectively, the observer can view all the external-scene image passing through the first and second surfaces and through the first and third surfaces. Accordingly, the field angle for observation of the external-scene image becomes wider than
25   the field angle for observation of the electronic image. Thus, a natural and wide external-scene image can be observed. Consequently, it is possible to provide a remarkably safe image display apparatus which enables the

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observer to avoid a dangerous situation and to cope appropriately with an emergency situation.

It is desirable for the second optical element to be capable of simultaneously canceling the composite power of the first and second surfaces and the composite power of the first and third surfaces with respect to external light. If the second optical element capable of simultaneously canceling the composite powers is formed from a single optical element and it is disposed on the outside world side of the ocular optical system, it is possible to observe the external scene over a wide range. Because the second optical element simultaneously cancels the composite powers, there is no break in the external-scene image. Thus, it is possible to observe an even more natural external-scene image. Accordingly, the external scene can be recognized over a wide range with a single optical element, and it is possible to provide an image display apparatus of reduced cost and enhanced safety which enables the observer to avoid a dangerous situation and to cope with an emergency situation.

The above-described image observation apparatus may have a device for positioning the image display device and the ocular optical system with respect to the observer's head. It becomes possible for the observer to see a stable electronic image by providing a device for positioning both the image display device and the ocular optical system with respect to the observer's head.

The image display apparatus may have a device for

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supporting both the image display device and the ocular
optical system with respect to the observer's head such that
the apparatus can be mounted on the observer's head. By
allowing both the image display device and the ocular

5   optical system to be mounted on the observer's head with a
supporting device, it becomes possible for the observer to
see the observation image in a desired posture and from a
desired direction.

Further, it is possible to provide a device for
10   supporting at least a pair of image display apparatuses at a
predetermined spacing. It becomes possible for the observer
to see the electronic image with both eyes without fatigue
by providing a device for supporting at least two image
display apparatuses at a predetermined spacing. Further, if
15   images with a disparity therebetween are displayed on the
right and left image display devices, and these images are
observed with both eyes, it is possible to enjoy viewing a
stereoscopic image.

The ocular optical system in the above-described image
20   display apparatus can be used as an image-forming optical
system. If the ocular optical system is arranged to form an
image of an object at infinity with the image display
surface in the ocular optical system defined as an image
plane, the ocular optical system can be used as an image-
25   forming optical system, e.g. a finder optical system for a
camera such as that shown in Fig. 24.

It should be noted that in the present invention, the
second and third surfaces may be formed from a single

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identical surface. In this case, the number of physical surfaces can be reduced by one, and it is therefore possible to simplify the process in terms of the optical design and the production of prism and hence possible to contribute to

5   the achievement of an increase in mass-productivity and reductions in costs. It is desirable that a physically single surface should be arranged to have both the functions of the second and third surfaces, and that internally reflecting regions should overlap each other. By doing so,

10   it is possible to realize a reduction in the size of the prism member.

Still other objects and advantages of the invention will in part be obvious and will in part be apparent from the specification.

15   The invention accordingly comprises the features of construction, combinations of elements, and arrangement of parts which will be exemplified in the construction hereinafter set forth, and the scope of the invention will be indicated in the claims.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 1 of the

25   present invention.

Fig. 2 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 2 of the

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present invention.

Fig. 3 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 3 of the

5   present invention.

Fig. 4 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 4 of the present invention.

10   Figs. 5(a) and 5(b) are sectional views for describing an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 5 of the present invention in comparison to a modification, in which Fig. 5(a) shows the

15   modification, and Fig. 5(b) shows Example 5.

Fig. 6 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 6 of the present invention.

20   Fig. 7 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 7 of the present invention.

Figs. 8(a), 8(b) and 8(c) are sectional views of an

25   optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 8 of the present invention.

Figs. 9(a), 9(b) and 9(c) are sectional views of an

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optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 9 of the present invention.

Fig. 10 is a sectional view of an optical system for a
5   single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 10 of the present invention.

Fig. 11 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which
10   uses an ocular optical system according to Example 11 of the present invention.

Fig. 12 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 12 of the
15   present invention.

Fig. 13 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 13 of the present invention.

20   Fig. 14 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 14 of the present invention.

Fig. 15 is a sectional view of an optical system for a
25   single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 15 of the present invention.

Fig. 16 is a sectional view of an optical system for a

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single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 16 of the present invention.

Fig. 17 is a sectional view of an optical system for a single eye of a head-mounted image display apparatus which uses an ocular optical system according to Example 17 of the present invention.

Fig. 18 is a sectional view of an ocular optical system arranged as in Example 17, which is provided with a line-of-sight detecting device.

Figs. 19(a), 19(b) and 19(c) show a mechanism for moving an ocular optical system arranged as in Example 17 to change observation positions from an electronic image observation position to an external-scene image observation position, and also show a direction of movement for changing the observation positions.

Figs. 20(a) and 20(b) are fragmentary sectional views for describing an action in which unwanted light is eliminated by a totally reflecting surface in the present invention.

Fig. 21 shows an image display apparatus according to the present invention which is arranged in the form of an image display apparatus for a single eye.

Fig. 22 shows an image display apparatus according to the present invention which is arranged in the form of an image display apparatus for both eyes.

Fig. 23 shows an arrangement of an optical system according to the present invention which is used as an

image-forming optical system.

Fig. 24 shows an arrangement of an optical system according to the present invention which is used as an image-forming optical system.

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DESCRIPTION OF THE PREFERRED EMBODIMENTS

Examples 1 to 17 of the image display apparatus according to the present invention will be described below.

In constituent parameters of each example (described later), as shown typically in Fig. 1, an exit pupil 1 of an ocular optical system 12 is defined as the origin of the optical system, and an optical axis 2 is defined by a light ray passing through both the center of the display area of an image display device 7 and the center (the origin) of the exit pupil 1. A Z-axis is taken in a direction in which light rays travel from the exit pupil 1 along the optical axis 2. A Y-axis is taken in a direction extending through the center of the exit pupil 1 at right angles to the Z-axis in a plane in which light rays are bent by the ocular optical system 12. An X-axis is taken in a direction extending through the center of the exit pupil 1 at right angles to both the Z- and Y-axes. A direction in which the Z-axis extends from the exit pupil 1 toward the ocular optical system 12 is defined as a positive direction of the Z-axis. A direction in which the Y-axis extends from the optical axis 2 toward the image display device 7 is defined as a positive direction of the Y-axis. A direction in which the X-axis constitutes a right-handed system in combination

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with the Z- and Y-axes is defined as a positive direction of the X-axis. It should be noted that ray tracing is carried out by backward tracing from the exit pupil 1 of the ocular optical system 12, which is defined as the object side,

5   toward the image display device 7, which is defined as the image plane side.

Regarding each surface for which displacements Y and Z and tilt angle θ are shown, the displacement Y is a distance by which the surface is displaced in the Y-axis direction

10   from the exit pupil 1, which is the origin of the optical system, while the displacement Z is a distance by which the surface is displaced in the Z-axis direction from the exit pupil 1, and the tilt angle θ is an angle of inclination of the center axis of the surface with respect to the Z-axis

15   unless otherwise specified in the constituent data (specified in Examples 6 and 9). It should be noted that, for the tilt angle, the counterclockwise direction is defined as a positive direction. In a case where a reference surface is particularly specified, displacements

20   and tilt angle are similarly given with respect to the vertex of the reference surface.

In the constituent parameters (shown later), the surface separation in the coaxial portion is shown as the distance from the surface concerned to the next surface. In

25   addition, the radius of curvature of each spherical surface, refractive index of each medium, and Abbe's number are given according to the conventional method.

Figs. 1 to 4 and 5(b) to 17 are sectional views of

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image display apparatuses according to Examples 1 to 4 and 5 to 17 of the present invention, taken along a plane containing the optical axis. In the examples shown in Figs. 1 to 4, 5(b) to 11, 15 and 16, the image display

5   apparatuses each comprise a decentered prism 12 in which a space formed by four surfaces 3, 4, 5 and 6 which are decentered with respect to the optical axis is filled with a medium having a refractive index larger than 1. In the example shown in Fig. 17, the image display apparatus

10   comprises a decentered prism 12 in which a space formed by three surfaces 3, 4 and 6 which are decentered with respect to the optical axis is filled with a medium having a refractive index larger than 1. In each figure, reference numeral 1 denotes an observer's pupil; 2 denotes an

15   observer's visual axis; 3 denotes a first surface of an ocular optical system 12; 4 denotes a second surface of the ocular optical system 12; 5 denotes a third surface of the ocular optical system 12; 6 denotes a fourth surface of the ocular optical system 12; 7 denotes an image display device;

20   8 denotes a Fresnel; 9 denotes a line-of-sight detecting optical system; 10 denotes a line-of-sight detector; 11 denotes an illuminating device; 12 denotes an ocular optical system (decentered prism); 13 and 14 denote second optical elements; 15 denotes an observer's eyeball; 16 denotes an

25   optical filter; 17 denotes a linear motor; 18 denotes projections provided on an optical element; and 19 denotes a guide (rail) provided on a casing. In the examples shown in Figs. 1 to 4, 5(b) to 11, 15 and 16, the actual path of

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light rays during the observation of the electronic image is
as follows: Light rays emitted from the electronic image of
the image display device 7 enter the ocular optical system
12 through the fourth surface 6, which is a refracting
5   surface disposed to face the image display device 7. The
incident light rays are reflected toward the observer's
pupil 1 by the third surface 5, which is adjacent to the
fourth surface 6 in the group of two surfaces 4 and 5
located on the side of the ocular optical system 12 that is
10   remote from the observer's face. The reflected light rays
are reflected so as to travel away from the observer's pupil
1 by the first surface 3, which is disposed immediately in
front of the observer's pupil 1. Then, the reflected light
rays are reflected toward the observer's pupil 1 by the
15   second surface 4, which is disposed immediately in front of
the observer's pupil 1 in the group of two surfaces 4 and 5
located on the side of the ocular optical system 12 that is
remote from the observer's face. The reflected light rays
pass through the first surface 3 and are projected into the
20   observer's eyeball 15 with the observer's iris position or
eyeball rolling center as an exit pupil 1. In Example 17
shown in Fig. 17, light rays emitted from the electronic
image of the image display device 7 enter the ocular optical
system 12 through the fourth surface 6, which is a
25   refracting surface disposed to face the image display device
7. The incident light rays are reflected toward the
observer's pupil 1 by that region (third surface 5) of the
second surface 4 which is adjacent to the fourth surface 6.

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The second surface 4 also serves as the third surface 5, which is located on the side of the ocular optical system 12 that is remote from the observer's face. The reflected light rays are reflected so as to travel away from the

5   observer's pupil 1 by the first surface 3, which is disposed immediately in front of the observer's pupil 1. Then, the reflected light rays are reflected toward the observer's pupil 1 by that region of the second surface 4 which is remote from the fourth surface 6 and located on the side of

10   the ocular optical system 12 that is remote from the observer's face. The reflected light rays pass through the first surface 3 and are projected into the observer's eyeball 15 with the observer's iris position or eyeball rolling center as an exit pupil 1.

15   Figs. 5(b) and 6 show examples of an image display apparatus according to the present invention that has a line-of-sight detecting device. The third surface 5, which is a reflecting surface disposed on the outside world side of the ocular optical system 12, is set so that a part of

20   the third surface 5 totally reflects light rays. The totally reflecting portion of the third surface 5 can reflect light from the image display device 7 without reflection coating. Therefore, no reflection coating is needed. The actual path of light rays during the detection

25   of the observer's line of sight is as follows: Illuminating light from the light source 11 passes through the third and first surfaces 5 and 3 of the ocular optical system 12 to illuminate the observer's eyeball 15. Light rays reflected

from the observer's eyeball 15 enter the ocular optical system 12 through the first surface 3, which is disposed immediately in front of the observer's pupil 1. The light rays pass through a totally reflecting region provided in at

5 least a part of the third surface 5, which is located on the side of the ocular optical system 12 that is remote from the observer's face. The light rays passing through the totally reflecting region of the third surface 5 are led to the line-of-sight detector 10 through the line-of-sight

10 detecting optical system 9 to form an image of the observer's pupil 1. To reduce the effect of light from the electronic image or the like, it is possible to use an infrared light illuminating device as the light source 11 and an infrared light detector as the line-of-sight detector

15 10. The position of the illuminating device 11 is not necessarily limited to the illustrated position. The illuminating device 11 may be disposed at any position, provided that the observer's eyeball 15 can be illuminated.

Fig. 18 is a sectional view of an arrangement in which

20 a line-of-sight detecting device similar to the above, which comprises a line-of-sight detecting optical system 9, a line-of-sight detector 10, and a light source 11, is provided in an ocular optical system 12 comprising three surfaces 3, 4 and 6 decentered with respect to the optical

25 axis as in Example 17. The actual path of light rays during the detection of the observer's line of sight is similar to that in the case of Figs. 5(b) and 6; therefore, a description thereof is omitted.

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Fig. 7 shows an example of an image display apparatus
according to the present invention that enables the
electronic image and the external-scene image to be
simultaneously observed through the ocular optical system
5   12. The actual path of light rays during the observation of
the external-scene image is as follows: Light rays from an
object point in the external scene enter the ocular optical
system 12 through the third surface 5, pass through the
first surface 3 and are projected into the observer's
10 eyeball 15 with the observer's iris position or eyeball
rolling center as an exit pupil 1. It may be made easy for
the observer to view either or both of the electronic image
and the external-scene image by disposing a light-reducing
filter or optical element 16 that controls the quantity of
15 external light at the outside world side of the third
surface 5. By moving the light-reducing filter or optical
element 16 between the observation ranges α and β, it is
possible to control the quantity of light from either of the
electronic image and the external-scene image.
20   Figs. 8(a), 8(b) and 8(c) and Figs. 9(a), 9(b) and 9(c)
show examples of another image display apparatus according
to the present invention that enables the external-scene
image to be observed by moving the ocular optical system 12.
In the example shown in Figs. 8(a), 8(b) and 8(c), the
25 ocular optical system 12 is moved from the electronic image
observation position shown in Fig. 8(a) in the negative
direction of the Y-axis relative to the observer's pupil 1
to reach the external-scene image observation position shown

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in Fig. 8(b). In the example shown in Figs. 9(a), 9(b) and 9(c), the ocular optical system 12 is rotated clockwise relative to the observer's pupil 1 from the electronic image observation position shown in Fig. 9(a) to reach the

5   external-scene image observation position shown in Fig. 9(b). Therefore, in either case, the external scene can be observed in the direction of the observer's visual axis. Light rays from an object point in the external scene enter the ocular optical system 12 through the third surface

10   5, pass through the first surface 3 and are projected into the observer's eyeball with the observer's iris position or eyeball rolling center as an exit pupil 1. In the position shown in Fig. 8(b), the observer can view the electronic image in a region below the observer's visual axis 2. The

15   direction of observation of the electronic image differs depending on the way in which the ocular optical system 12 is disposed and the direction in which the ocular optical system 12 is moved. Therefore, the observation of the electronic image may be performed in any direction.

20   Figs. 8(c) and 9(c) show examples of a mechanism for moving the ocular optical system 12. In either case, the ocular optical system 12 is moved along a guide (rail) 19 provided on the casing by a linear motor 17 through projections 18 provided on the optical element. In the case

25   of Fig. 8(c), the guide (rail) 19 is rectilinear. Therefore, the ocular optical system 12 is moved rectilinearly. In the case of Fig. 9(c), the guide (rail) 19 is arcuate. Therefore, the ocular optical system 12 is

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rotated.

Figs. 19(a), 19(b) and 19(c) show an example in which
an ocular optical system 12 comprising three surfaces 3, 4
and 5 decentered with respect to the optical axis as in
Example 17 is moved from the electronic image observation
position in the negative direction of the Y-axis relative to
the observer's pupil 1 to reach the external-scene image
observation position as in the case of the example shown in
Figs. 8(a), 8(b) and 8(c). The operation of this example is
similar to that of the example shown in Figs. 8(a), 8(b) and
8(c). Therefore, a description thereof is omitted.

Figs. 10 to 14 show examples of an image display
apparatus according to the present invention in which a
Fresnel lens 8 serving as an aberration correcting device is
disposed in an optical path for observation of the external-
scene image. The actual path of light rays during the
observation of the external-scene image is as follows: Light
rays from an object point in the external scene pass through
the Fresnel lens 8 and enter the decentered prism 12 through
the second surface 4. Then, the light rays pass through the
first surface 3 and are projected into the observer's
eyeball with the observer's iris position or eyeball rolling
center as an exit pupil 1. In this arrangement, the Fresnel
lens 8 is only necessary to dispose at a predetermined
position when the external scene is observed. When the
observer does not want to view the external scene, the
Fresnel lens 8 is moved to another position by a moving
mechanism, e.g. a mechanism for moving the Fresnel lens 8

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vertically, or a mechanism for rotating the Fresnel lens 8.
Alternatively, the Fresnel lens 8 may be arranged to be
detachable.

In the examples shown in Figs. 10 to 14, those which

5   are shown in Figs. 10 and 11 are arranged as in the case of
Fig. 1. That is, the ocular optical system (decentered
prism) 12 comprises four surfaces 3, 4, 5 and 6 decentered
with respect to the optical axis, and when the electronic
image is observed, light rays travel along the same path as

10   in the case of Fig. 1. However, the ocular optical system
shown in Fig. 12 comprises a decentered prism 12 in which
a space formed by three surfaces 3, 4 and 6 decentered
with respect to the optical axis is filled with a medium
having a refractive index larger than 1. The actual path of

15   light rays during the observation of the electronic image is
as follows: Light rays emitted from the electronic image of
the image display device 7 enter the ocular optical system
12 through the fourth surface (the third surface as counted
in the sequence of surfaces) 6, which is a refracting surface

20   disposed to face the image display device 7. The incident
light rays are reflected so as to travel away from the
observer's pupil 1 by the first surface 3, which is disposed
immediately in front of the observer's pupil 1. The
reflected light rays are reflected toward the observer's

25   pupil 1 by the second surface 4, which is disposed on the
side of the ocular optical prism 12 that is remote from the
observer's face. Then, the reflected light rays pass
through the first surface 3 and are projected into the

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observer's eyeball 15 with the observer's iris position or eyeball rolling center as an exit pupil 1.

The ocular optical system shown in Fig. 13 comprises a decentered prism 12 in which a space formed by three surfaces 3, 4 and 6 decentered with respect to the optical axis is filled with a medium having a refractive index larger than 1. The actual path of light rays during the observation of the electronic image is as follows: Light rays emitted from the electronic image of the image display device 7 enter the ocular optical system 12 through the fourth surface (the third surface as counted in the sequence of surfaces) 6, which is a refracting surface disposed to face the image display device 7. The incident light rays are reflected toward the observer's pupil 1 by the second surface 4, which is disposed on the side of the ocular optical system 12 that is remote from the observer's face. The reflected light rays pass through the first surface 3 and are projected into the observer's eyeball 15 with the observer's iris position or eyeball rolling center as an exit pupil 1.

The ocular optical system 12 shown in Fig. 14 comprises a decentered prism 12 in which a space formed by two surfaces 3 and 4 decentered with respect to the optical axis is filled with a medium having a refractive index larger than 1. The actual path of light rays during the observation of the electronic image is as follows: Light rays emitted from the electronic image of the image display device 7 enter the ocular optical system 12 through the

first surface 3, which is a refracting surface disposed to face the image display device 7. The incident light rays are reflected toward the observer's pupil 1 by the second surface 4, which is located on the side of the ocular optical system 12 that is remote from the observer's face. The reflected light rays pass through the first surface 3 and are projected into the observer's eyeball 15 with the observer's iris position or eyeball rolling center as an exit pupil 1.

Figs. 15 and 16 show examples of an image display apparatus according to the present invention which is adapted to observe the external scene through the first surface 3 of the ocular optical system 12, which is located immediately in front of the observer's eyeball, and further through either of the second and third surfaces 4 and 5 of the ocular optical system 12, which are outside world-side internally reflecting surfaces. When the external scene is to be observed, second optical elements 13 and 14, which are adapted to cancel powers produced by the two surfaces 3 and 4 or 3 and 5 with respect to external light, are disposed in the optical paths for observation of the external-scene image. The actual path of light rays during the observation of the external-scene image is as follows: Light rays from an object point in the external scene pass through a second optical element 13 or another second optical element 14 and enter the decentered prism 12 through the second surface 4 or the third surface 5. Then, the light rays pass through the first surface 3 and are projected into the observer's

eyeball 15 with the observer's iris position or eyeball rolling center as an exit pupil 1.

It should be noted that the present invention is not necessarily limited to the optical systems shown in Figs. 1 to 4 and 5(b) to 19 but may also be applied to other known optical systems.

In the constituent parameters of each of the following examples, the rotationally symmetric aspherical configuration of each surface may be given by the following equation on the assumption that the paraxial curvature radius is denoted by R. The Z-axis is the axis of the rotationally symmetric aspherical surface.

$$Z=(h^2/R)/[1+\{1-(1+K)(h^2/R^2)\}^{1/2}]$$
$$+Ah^4+Bh^6+Ch^8+Dh^{10}\ldots$$
$$(h^2=x^2+y^2)$$

...(a)

where Z is the amount of deviation from a plane tangent to the origin of the surface configuration; K is the conical coefficient; and A, B, C and D are 4th-, 6th-, 8th- and 10th-order aspherical coefficients, respectively.

The configuration of an anamorphic surface is defined by the following equation. A straight line which passes through the origin of the surface configuration and which is perpendicular to the optical surface is defined as the axis of the anamorphic surface.

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$$z = (CX \cdot x^2 + CY \cdot y^2) / [1 + \{1 - (1+K_x)CX^2 \cdot x^2$$

$$- (1+K_y)CY^2 \cdot y^2\}^{1/2}]$$

$$+ \sum_{m=1} R_m \{(1-P_m)x^2 + (1+P_m)y^2\}^{m+1}$$

Assuming that m=4 (polynomial of degree 4), for example, the equation, when expanded, may be given by:

$$z = (CX \cdot x^2 + CY \cdot y^2) / [1 + \{1 - (1+K_x)CX^2 \cdot x^2$$
$$- (1+K_y)CY^2 \cdot y^2\}^{1/2}]$$
$$+ R_1 \{(1-P_1)x^2 + (1+P_1)y^2\}^2$$
$$+ R_2 \{(1-P_2)x^2 + (1+P_2)y^2\}^3$$
$$+ R_3 \{(1-P_3)x^2 + (1+P_3)y^2\}^4$$
$$+ R_4 \{(1-P_4)x^2 + (1+P_4)y^2\}^5$$

...(b)

where z is the amount of deviation from a plane tangent to the origin of the surface configuration; CX is the curvature in the X-axis direction; CY is the curvature in the Y-axis direction; K_x is the conical coefficient in the X-axis direction; K_y is the conical coefficient in the Y-axis direction; R_m is the rotationally symmetric component of the aspherical surface term; and P_m is the rotationally asymmetric component of the aspherical surface term. It should be noted that in the constituent parameters of the examples (described later), the following parameters are employed:

R_x: the radius of curvature in the X-axis direction

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R_y: the radius of curvature in the Y-axis direction

The curvature radii are related to the curvatures CX and CY as follows:

$R_x = 1/CX$, $R_y = 1/CY$

5   The configuration of a three-dimensional surface is defined by the following equation. The Z-axis of the defining equation is the axis of the three-dimensional surface.

10

$$Z = \sum_{n=0}^{k} \sum_{m=k}^{n} C_{nm} X^n Y^{n-m}$$

Assuming that k=7 (polynomial of degree 7), for
15   example, a three-dimensional surface is expressed by an expanded form of the above equation as follows:

$$Z = C_2$$
$$+C_3Y+C_4X$$
$$+C_5Y^2+C_6YX+C_7X^2$$
20
$$+C_8Y^3+C_9Y^2X+C_{10}YX^2+C_{11}X^3$$
$$+C_{12}Y^4+C_{13}Y^3X+C_{14}Y^2X^2+C_{15}YX^3+C_{16}X^4$$
$$+C_{17}Y^5+C_{18}Y^4X+C_{19}Y^3X^2+C_{20}Y^2X^3+C_{21}YX^4$$
$$+C_{22}X^5$$
$$+C_{23}Y^6+C_{24}Y^5X+C_{25}Y^4X^2+C_{26}Y^3X^3+C_{27}Y^2X^4$$
25
$$+C_{28}YX^5+C_{29}X^6$$
$$+C_{30}Y^7+C_{31}Y^6X+C_{32}Y^5X^2+C_{33}Y^4X^3+C_{34}Y^3X^4$$
$$+C_{35}Y^2X^5+C_{36}YX^6+C_{37}X^7$$

...(c)

In the examples of the present invention, each ocular optical system is designed as an optical system symmetric with respect to the X-axis direction. Therefore, the coefficients of the terms with odd-numbered powers of X are

5   set equal to zero [in the above equation (c), C_4, C_6, C_9, ...=0].

In the constituent parameters (shown later), those terms concerning aspherical surfaces for which no data is shown are zero. The refractive index is expressed by the

10   refractive index for the spectral d-line (wavelength: 587.56 nanometers). Lengths are given in millimeters.

Figs. 1 to 4 and 5(b) to 17 are sectional views of Examples 1 to 4 and 5 to 17 taken along the YZ-plane containing the optical axis 2. In Examples 1 to 11, 13 and

15   14, the observation field angles are as follows: The horizontal field angle is 30.0°, and the vertical field angle is 22.72°. In Example 12, the observation field angles are as follows: The horizontal field angle is 40.0°, and the vertical field angle is 30.53°. In Examples 15 and

20   16, the observation field angles are as follows: The horizontal field angle is 35.0°, and the vertical field angle is 26.60°. In Examples 1 to 16, the pupil diameter is 4 millimeters.

The constituent parameters and the values of the

25   conditions in the above-described Examples 1 to 6, 9 to 14 and 17 are shown below. The constituent parameters of Examples 7 and 8 are the same as those of Example 3; therefore, a description thereof is omitted. The

constituent parameters of Examples 10 and 11 during the
observation of the image display device are the same as
those of Example 5. Therefore, the constituent parameters
during the observation of the external scene are shown for

5   Examples 10 and 11. The constituent parameters of Example
12 during the observation of the image display device are
shown under "Example 12(1)". The constituent parameters of
Example 12 during the observation of the external scene are
shown under "Example 12(2)". It should be noted that in the

10   table below, "ASPH" denotes an aspherical surface; "ANAM"
denotes an anamorphic surface; "SF" denotes a surface; and
"REFL" denotes a reflecting surface.

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Example 1

Surface No.	Radius of curvature	Surface separation	Refractive index (Displacement)	Abbe's No. (Tilt angle)

1   ∞(Pupil)

2 ASPH ∞ 1.5254   56.25

(1ST SF) K   0.0000   Y   18.114 θ 4.44°

         A   0.0000   Z   37.091

         B   0.0000

         C 1.1599×10^{-13}

         D 4.4930×10^{-16}

3 ANAM R_y -142.541 1.5254   56.25

(2ND SF) R_x -122.057 Y   3.041 θ $-17.79°$

(REFL) K_y -5.4587 Z   52.132

         K_x -0.2658

         R_1 -5.0900×10^{-10}

         R_2 3.0528×10^{-10}

         R_3 6.2600×10^{-13}

         R_4 4.9434×10^{-15}

         P_1 $-1.1948 \times 10^{+1}$

         P_2 2.3791×10^{-1}

         P_3 4.8713×10^{-1}

         P_4 3.3074×10^{-1}

4 ASPH ∞ 1.5254   56.25

(1ST SF) K   0.0000   Y   18.114 θ 4.44°

(REFL)   A   0.0000   Z   37.091

         B   0.0000

         C 1.1599×10^{-13}

		D	4.4930 $\times 10^{-16}$				

5			∞		1.5254		56.25

(3RD SF)   Y   18.114 θ 4.44°

(REFL)   Z   53.502

6 ANAM R_y 47.391   Y   41.220 θ -55.16°

(4TH SF) R_x 86.005   Z   47.787

K_y 1.9910

K_x -0.1607

R_1 1.1694 $\times 10^{-7}$

R_2 -2.2052 $\times 10^{-10}$

R_3 -1.8410 $\times 10^{-11}$

R_4 -4.2076 $\times 10^{-14}$

P_1 -6.2804

P_2 -4.0710

P_3 4.2066 $\times 10^{-1}$

P_4 5.1697 $\times 10^{-1}$

7   ∞ Y   40.079 θ -25.63°

(Image display plane)   Z   38.041

(1) $\theta_{r3} = 43.85°$

(3) $\phi_{t1}(yz) = 0$ (1/mm)

$\phi_{t1}(xz) = 0$ (1/mm)

Example 2

Surface No.	Radius of curvature	Surface separation	Refractive index	Abbe's No.
			(Displacement)	(Tilt angle)
1	∞(Pupil)			
2	Three-dimensional surface(1)		1.5000	55.55

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| | | | | Y | 8.738 | θ | −0.43° |
| | | | | Z | 38.294 | | |

(1ST SF)

| | | | | | 1.5000 | | 55.55 |
3 Three-dimensional surface(2)

(2ND SF)

| | | | | Y | 0.000 | θ | −26.39° |

(REFL)

| | | | | Z | 47.232 | | |

| | | | | | 1.5000 | | 55.55 |
4 Three-dimensional surface(1)

| | | | | Y | 8.738 | θ | −0.43° |
(1ST SF)

(REFL)

| | | | | Z | 38.294 | | |

| | | | | | 1.5000 | | 55.55 |
5 Three-dimensional surface(3)

| | | | | Y | 28.900 | θ | 4.00° |
(3RD SF)

(REFL)

| | | | | Z | 51.503 | | |

| | | | | | 1.5000 | | 55.55 |
6 Three-dimensional surface(4)

| | | | | Y | 37.094 | θ | −42.91° |
(4TH SF)

| | | | | Z | 43.146 | | |

| | | | | Y | 39.222 | θ | −39.45° |

7 ∞

| | | | | Z | 41.032 | | |

(Image display plane)

Three-dimensional surface(1)

C_5 −4.3507×10^{-4} C_7 −8.3810×10^{-3} C_8 −7.2046×10^{-5}

C_{10} −1.6070×10^{-4} C_{12} −5.7849×10^{-7} C_{14} −7.6285×10^{-7}

C_{16} 2.6344×10^{-6} C_{17} −7.4711×10^{-9} C_{19} −1.9337×10^{-8}

C_{21} 9.3990×10^{-8}

Three-dimensional surface(2)

C_5 −4.4979×10^{-3} C_7 −8.5757×10^{-3} C_8 −6.4211×10^{-5}

C_{10} −3.1176×10^{-5} C_{12} 1.3495×10^{-6} C_{14} 4.8979×10^{-8}

C_{16} −2.4100×10^{-8} C_{17} −4.2204×10^{-8} C_{19} −3.8212×10^{-8}

C_{21} −9.1979×10^{-9}

Three-dimensional surface(3)

C_5 −4.6997×10^{-4} C_7 −3.2125×10^{-3} C_8 −8.6078×10^{-5}

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C_{10} -1.0181×10^{-4} C_{12} -2.7246×10^{-6} C_{14} 2.7277×10^{-6}

C_{16} 3.7002×10^{-6} C_{17} -3.1103×10^{-8} C_{19} 1.0092×10^{-8}

C_{21} 2.0208×10^{-7}

Three-dimensional surface(4)

C_{5} 3.6987×10^{-3} C_{7} 8.3763×10^{-3} C_{8} -8.9771×10^{-4}

C_{10} 5.0916×10^{-6} C_{12} -5.7678×10^{-5} C_{14} 4.5123×10^{-7}

C_{16} -2.3865×10^{-6}

(1) $\theta_{r3} = 48.44°$

(3) $\phi_{t1}(yz) = -0.0037 \ (1/mm)$

$\phi_{t1}(xz) = -0.0072 \ (1/mm)$

Example 3

Surface No.	Radius of curvature	Surface separation	Refractive index (Displacement)	Abbe's No. (Tilt angle)
1	∞(Pupil)			
2	∞		1.5254	56.25
(1ST SF)			Y -27.000 θ	0.00°
			Z 37.395	
3 ANAM	R_y -143.929		1.5254	56.25
(2ND SF)	R_x -123.293		Y -14.868 θ	-28.80°
(REFL)	K_y 0.3713		Z 42.871	
	K_x -1.9942			
	R_1 2.1403×10^{-8}			
	R_2 9.6413×10^{-13}			
	R_3 6.3684×10^{-14}			
	R_4 -1.2452×10^{-17}			
	P_1 -3.9989×10^{-3}			

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P_2	-3.0463			
P_3	$2.5677 \times 10-1$			
P_4	$4.2810 \times 10-1$			

4	∞			
(1ST SF)			1.5254	56.25
(REFL)		Y -27.000	θ	0.00°
5	∞	Z 37.395		
(3RD SF)			1.5254	56.25
(REFL)		Y 0.079	θ	0.00°
6 ANAM	R_y 39.861	Z 53.539		
(4TH SF)	R_x 62.319	Y 44.498	θ	-66.77°
	K_y 1.5656	Z 51.066		
	K_x 4.2425			
	R_1 3.9064×10^{-6}			
	R_2 5.0520×10^{-10}			
	R_3 4.9921×10^{-13}			
	R_4 -6.6158×10^{-15}			
	P_1 -1.5408×10^{-1}			
	P_2 4.0979			
	P_3 1.6631			
	P_4 1.0506			

7	∞	Y 42.800	θ	-21.40°
(Image display plane)		Z 38.475		

$(1)\ \theta_{r3} = 44.53°$

$(3)\ \phi_{t1}\ (yz) = 0\ (1/mm)$

$\phi_{t1}\ (xz) = 0\ (1/mm)$

Example 4

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Surface No.	Radius of curvature	Surface separation	Refractive index	Abbe's No.
			(Displacement)	(Tilt angle)
1	∞(Pupil)			
2 ANAM	R_y -242.348		1.5254	56.25
(1ST SF)	R_x -159.768	Y 5.082	θ	-3.86°
	K_y 12.1104	Z 32.396		
	K_x 4.7358			
	R_1 -2.5719 $\times 10^{-10}$			
	R_2 -4.9792 $\times 10^{-12}$			
	R_3 8.8695 $\times 10^{-13}$			
	R_4 6.7191 $\times 10^{-20}$			
	P_1 -1.8150 $\times 10^{+1}$			
	P_2 -4.7838			
	P_3 -1.2978			
	P_4 -7.1284			
3 ANAM	R_y -119.562		1.5254	56.25
(2ND SF)	R_x -98.451	Y 27.149	θ	-11.26°
(REFL)	K_y -0.1186	Z 52.500		
	K_x 0.7866			
	R_1 -1.6969 $\times 10^{-9}$			
	R_2 -6.2266 $\times 10^{-11}$			
	R_3 8.5459 $\times 10^{-16}$			
	R_4 8.0998 $\times 10^{-16}$			
	P_1 -1.8331			
	P_2 -4.9789 $\times 10^{-1}$			
	P_3 -2.3604			
	P_4 -9.6450 $\times 10^{-1}$			

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4 ANAM R_y -242.348

(1ST SF) R_x -159.768

(REFL) K_y 12.1104

           K_x 4.7358

           R_1 -2.5719 $\times 10^{-10}$

           R_2 -4.9792 $\times 10^{-12}$

           R_3 8.8695 $\times 10^{-13}$

           R_4 6.7191 $\times 10^{-20}$

           P_1 -1.8150 $\times 10^{+1}$

           P_2 -4.7838

           P_3 -1.2978

           P_4 -7.1284

5 ANAM R_y -179.007

(3RD SF) R_x -231.111

(REFL) K_y 2.2288

           K_x -72.7188

           R_1 6.1912 $\times 10^{-8}$

           R_2 -9.4470 $\times 10^{-13}$

           R_3 2.8064 $\times 10^{-15}$

           R_4 2.0069 $\times 10^{-18}$

           P_1 2.0705 $\times 10^{-2}$

           P_2 6.7667

           P_3 -5.5003

           P_4 -4.0534

6 ANAM R_y 72.293

(4TH SF) R_x 39.167

           K_y -1.0213

           K_x -7.8305

          1.5254   56.25

Y   5.082 θ -3.86°

Z   32.396

          1.5254   56.25

Y   27.820 θ 1.74°

Z   47.835

Y   42.329 θ -42.24°

Z   43.924

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R_1 -7.5404×10^{-7}

R_2 -5.8510×10^{-10}

R_3 5.8345×10^{-13}

R_4 1.5291×10^{-15}

P_1 -1.2077×10^{-1}

P_2 2.1174×10^{-2}

P_3 2.9220×10^{-1}

P_4 -1.4519

7	∞		Y	42.878	θ -19.36°
(Image display plane)			Z	30.211	

(1) $\theta_{r3} = 42.75°$

(3) $\phi_{t1}(yz) = 0.0008\ (1/\text{mm})$

   $\phi_{t1}(xz) = -0.001\ (1/\text{mm})$

Example 5

Surface No.	Radius of curvature	Surface separation	Refractive index (Displacement)	Abbe's No. (Tilt angle)
1	∞(Pupil)			
2	-104.851		1.5254	56.25
(1ST SF)			Y 2.540	θ -7.02°
			Z 33.527	
3 ANAM R_y -54.751			1.5254	56.25
(2ND SF) R_x -62.006			Y -19.747	θ -48.21°
(REFL) K_y -1.3614			Z 30.166	
K_x 0.1944				
R_1 2.4430×10^{-10}				
R_2 -1.1189×10^{-10}				

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R_3 -2.4892×10^{-16}

R_4 1.9084×10^{-22}

P_1 $-2.7674 \times 10^{+1}$

P_2 5.3845×10^{-1}

P_3 -4.1468

P_4 $1.0048 \times 10^{+1}$

4   -104.851

(1ST SF)

(REFL)

5 ANAM R_y -8201.935

(3RD SF) R_x 1243.857

(REFL) K_y 0.0000

K_x 0.0000

R_1 9.7227×10^{-8}

R_2 1.2246×10^{-12}

R_3 -1.5956×10^{-16}

R_4 6.7677×10^{-21}

P_1 8.5858×10^{-1}

P_2 -4.4664

P_3 1.9991

P_4 2.2019

6   46.674

(4TH SF)

7   ∞

(Image display plane)

(1) $\theta_{r3} = 36.51°$

Example 6

1.5254   56.25

Y   2.540 θ $-7.02°$

Z   33.527

1.5254   56.25

Y -37.497 θ $4.95°$

Z   53.061

Y   28.160 θ $-29.19°$

Z   36.643

Y   31.793 θ $-26.09°$

Z   35.135

Surface No.	Radius of curvature		Surface separation	Refractive index	Abbe's No.
				(Displacement)	(Tilt angle)
1	∞(Pupil)				
2	∞			Y 0.000	θ 20.00°
(Hypothetic plane)				Z 0.000	
3	∞			1.5254	56.25
(1ST SF)				(from hypothetic plane)	
				Y 0.000	θ 0.00°
				Z 40.495	
4 ANAM	R_y	-146.661		1.5254	56.25
(2ND SF)	R_x	-131.067		(from hypothetic plane)	
(REFL)	K_y	-0.1158		Y -23.006	θ -32.35°
	K_x	-0.6570		Z 49.040	
	R_1	1.4710×10^{-8}			
	R_2	2.4181×10^{-10}			
	R_3	8.0445×10^{-14}			
	R_4	-1.0655×10^{-16}			
	P_1	-6.7968×10^{-1}			
	P_2	1.1524×10^{-2}			
	P_3	9.6151×10^{-1}			
	P_4	5.6260×10^{-1}			
5	∞			1.5254	56.25
(1ST SF)				(from hypothetic plane)	
(REFL)				Y 0.000	θ 0.00°
				Z 40.495	
6	∞			1.5254	56.25
(3RD SF)				(from hypothetic plane)	

(REFL)

7 ANAM	R_y	70.881
(4TH SF)	R_x	99.816
	K_y	6.0488
	K_x	7.1389
	R_1	1.8385×10^{-5}
	R_2	1.8499×10^{-10}
	R_3	-3.4116×10^{-12}
	R_4	-7.2747×10^{-15}
	P_1	3.2623×10^{-1}
	P_2	3.8697
	P_3	9.0201×10^{-1}
	P_4	1.1638×10^{-1}

| Y | 0.000 | θ | 0.00° |
| Z | 56.475 | | |

(from hypothetic plane)

| Y | 30.811 | θ | -80.98° |
| Z | 62.245 | | |

8   ∞

(Image display plane)

(1) $\theta_{r3} = 46.70°$

(3) $\phi_{t1} (yz) = 0 \ (1/\text{mm})$

   $\phi_{t1} (xz) = 0 \ (1/\text{mm})$

| Y | 40.634 | θ | -2.65° |
| Z | 30.403 | | |

Example 9

Surface No.	Radius of curvature	Surface separation	Refractive index	Abbe's No.
		(Displacement)	(Tilt angle)	
1	∞(Pupil)			
2	∞	Y 0.000 θ 15.00°		
(Hypothetic plane)		Z 0.000		
3	-221.433		1.5254	56.25

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(1ST SF)

(from hypothetic plane)

Y   0.000 θ 0.00°

Z   38.879

4   -106.803

1.5254   56.25

(2ND SF)

(from hypothetic plane)

(REFL)

Y   -16.310 θ -30.86°

Z   48.157

5   -221.433

1.5254   56.25

(1ST SF)

(from hypothetic plane)

(REFL)

Y   0.000 θ 0.00°

Z   38.879

6   -208.964

1.5254   56.25

(3RD SF)

(from hypothetic plane)

(REFL)

Y   0.000 θ 0.00°

Z   55.417

7   154.685

(from hypothetic plane)

(4TH SF)

Y   22.393 θ -20.71°

Z   41.581

8   ∞

Y   39.534 θ -5.00°

(Image display plane)

Z   27.732

(1) $\theta_{r3} = 41.68°$

(3) $\phi_{t1}(yz) = 0.00024 \ (1/mm)$

$\phi_{t1}(xz) = 0.00024 \ (1/mm)$

Example 10

Surface No.	Radius of curvature	Surface separation	Refractive index	Abbe's No.
		(Displacement)	(Tilt angle)	

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1   ∞(Pupil)

2   −104.851   1.5254   56.25

(1ST SF)   Y   2.540 θ −7.02°

      Z   33.527

3 ANAM R_y −54.751   Y   −19.747 θ −48.21°

(2ND SF) R_x −62.006   Z   30.167

(REFL) K_y −1.3614

        K_x 0.1944

        R_1 2.4430×10^{-10}

        R_2 -1.1189×10^{-10}

        R_3 -2.4892×10^{-16}

        R_4 1.9084×10^{-22}

        P_1 $-2.7674 \times 10^{+1}$

        P_2 5.3845×10^{-1}

        P_3 −4.1468

        P_4 $1.0048 \times 10^{+1}$

4   ∞   2.000   1.4922   57.50

(Fresnel-lens's first surface)   Y   45.000 θ 0.00°

      Z   51.527

5   ∞

(Fresnel-lens's second surface)

        K   0.0000

        A 2.0658×10^{-6}

        B -4.2780×10^{-10}

        C 3.2196×10^{-14}

        D 2.1256×10^{-18}

Example 11

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Surface No.	Radius of curvature		Surface separation	Refractive index (Displacement)	Abbe's No. (Tilt angle)
1	∞ (Pupil)				
2 (1ST SF)	-104.851			1.5254	56.25
				Y 2.540	θ $-7.02°$
				Z 33.527	
3 ANAM	R_y	-54.751		Y -19.747	θ $-48.21°$
(2ND SF)	R_x	-62.006		Z 30.166	
(REFL)	K_y	-1.3614			
	K_x	0.1944			
	R_1	2.4430×10^{-10}			
	R_2	-1.1189×10^{-10}			
	R_3	-2.4892×10^{-16}			
	R_4	1.9084×10^{-22}			
	P_1	$-2.7674 \times 10^{+1}$			
	P_2	5.3845×10^{-1}			
	P_3	-4.1468			
	P_4	$1.0048 \times 10^{+1}$			
4 (Fresnel-lens's first surface)	∞		2.000	1.4922 Y 20.000	57.50 θ $-22.00°$
				Z 53.527	
5 (Fresnel-lens's second surface)	∞				
	K	0.0000			
	A	4.4111×10^{-5}			
	B	-1.0534×10^{-7}			
	C	1.1649×10^{-10}			

D -4.9416×10^{-14} o

Example 1 2 (1)

Surface No.	Radius of curvature	Surface separation	Refractive index (Displacement)	Abbe's No. (Tilt angle)
1	∞(Pupil)			
2	Three-dimensional surface(1)		1.5254	56.25
(1ST SF)		Y 13.983	θ	9.46°
		Z 33.974		
3	Three-dimensional surface(2)		1.5254	56.25
(2ND SF)		Y 4.596	θ	-15.22°
(REFL)		Z 49.231		
4	Three-dimensional surface(1)		1.5254	56.25
(1ST SF)		Y 13.983	θ	9.46°
(REFL)		Z 33.974		
5	Three-dimensional surface(3)	Y 27.094	θ	79.39°
(3RD SF)		Z 35.215		
6	∞	Y 29.266	θ	46.34°
(Image display plane)		Z 46.318		

Three-dimensional surface(1)

C_5 -2.6152×10^{-3}	C_7 -3.9706×10^{-3}	C_8 -7.5434×10^{-5}
C_{10} -1.5120×10^{-6}	C_{12} 2.6572×10^{-7}	C_{14} 1.3359×10^{-6}
C_{16} 1.7946×10^{-7}	C_{17} -2.9881×10^{-9}	C_{19} -3.0362×10^{-9}
C_{21} -2.0258×10^{-7}	C_{23} -3.8978×10^{-10}	C_{25} 1.4986×10^{-9}
C_{27} -3.8974×10^{-9}	C_{29} -2.5335×10^{-9}	C_{30} 4.3101×10^{-12}
C_{32} -1.4923×10^{-11}	C_{34} 7.6026×10^{-11}	C_{36} -4.2410×10^{-11}

Three-dimensional surface(2)

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C_5 -6.2524×10^{-3} C_7 -7.5944×10^{-3} C_8 -1.0605×10^{-5}

C_{10} 9.3276×10^{-6} C_{12} 8.3882×10^{-7} C_{14} -5.6861×10^{-7}

C_{16} -4.9904×10^{-7} C_{17} -2.0403×10^{-10} C_{19} -8.0184×10^{-9}

C_{21} -4.4196×10^{-8} C_{23} 4.4149×10^{-10} C_{25} 3.8170×10^{-10}

C_{27} 8.4970×10^{-11} C_{29} -2.8006×10^{-10} C_{30} 1.3964×10^{-12}

C_{32} -1.7677×10^{-10} C_{34} 3.3220×10^{-12} C_{36} 6.9401×10^{-12}

Three-dimensional surface(3)

C_5 -1.2118×10^{-2} C_7 -3.7062×10^{-3} C_8 -1.2290×10^{-4}

C_{10} 9.9763×10^{-4} C_{12} -8.0746×10^{-5} C_{14} -3.8939×10^{-5}

C_{16} 2.6861×10^{-5} C_{17} -1.7720×10^{-6} C_{19} -3.4243×10^{-6}

C_{21} -3.5310×10^{-7} C_{23} 1.2185×10^{-7} C_{25} 1.0019×10^{-7}

C_{27} 1.4838×10^{-7} C_{29} -5.3531×10^{-8}

Example 1 2 (2)

Surface No.	Radius of curvature	Surface separation	Refractive index (Displacement)	Abbe's No. (Tilt angle)
1	∞(Pupil)			
2	Three-dimensional surface(1)		1.5254	56.25
(1ST SF)			Y 13.983	θ 9.46°
			Z 33.974	
3	Three-dimensional surface(2)		Y 4.596	θ -15.22°
(2ND SF)			Z 49.231	
4	∞	2.000	1.4922	57.50
(Fresnel-lens's first surface)			Y 45.982	θ -18.17°
			Z 65.000	
5	∞			
(Fresnel-lens's second surface)				

K 0.0000

A 3.9372×10^{-6}

B -1.6979×10^{-9}

C 4.2377×10^{-13}

D -4.1829×10^{-17}

Three-dimensional surface(1)

C_5 -2.6152×10^{-3}	C_7 -3.9706×10^{-3}	C_8 -7.5434×10^{-5}
C_{10} -1.5120×10^{-6}	C_{12} 2.6572×10^{-7}	C_{14} 1.3359×10^{-6}
C_{16} 1.7946×10^{-7}	C_{17} -2.9881×10^{-9}	C_{19} -3.0362×10^{-9}
C_{21} -2.0258×10^{-7}	C_{23} -3.8978×10^{-10}	C_{25} 1.4986×10^{-9}
C_{27} -3.8974×10^{-9}	C_{29} -2.5335×10^{-9}	C_{30} 4.3101×10^{-12}
C_{32} -1.4923×10^{-11}	C_{34} 7.6026×10^{-11}	C_{36} -4.2410×10^{-11}

Three-dimensional surface(2)

C_5 -6.2524×10^{-3}	C_7 -7.5944×10^{-3}	C_8 -1.0605×10^{-5}
C_{10} 9.3276×10^{-6}	C_{12} 8.3882×10^{-7}	C_{14} -5.6861×10^{-7}
C_{16} -4.9904×10^{-7}	C_{17} -2.0403×10^{-10}	C_{19} -8.0184×10^{-9}
C_{21} -4.4196×10^{-8}	C_{23} 4.4149×10^{-10}	C_{25} 3.8170×10^{-10}
C_{27} 8.4970×10^{-11}	C_{29} -2.8006×10^{-10}	C_{30} 1.3964×10^{-12}
C_{32} -1.7677×10^{-10}	C_{34} 3.3220×10^{-12}	C_{36} 6.9401×10^{-12}

Example 1 3

Surface No.	Radius of curvature	Surface separation	Refractive index (Displacement)	Abbe's No. (Tilt angle)
1	∞(Pupil)			
2	Three-dimensional surface(1)		1.5163	64.15
(1ST SF)			Y 0.000 θ	24.79°
			Z 35.567	

3	Three-dimensional surface(2)		1.5163	64.15
(2ND SF)		Y 5.402 θ -9.11°
(REFL)		Z 70.723
4	Three-dimensional surface(3)	Y 21.138 θ -25.12°
(3RD SF)		Z 39.783
5	∞	Y 23.963 θ -11.11°
(Image display plane)		Z 34.441

Three-dimensional surface(1)

C_5 6.8620×10^{-3} C_7 7.4153×10^{-3} C_8 5.9417×10^{-5}

C_{10} 2.9033×10^{-5} C_{12} -4.6823×10^{-7} C_{14} 3.8805×10^{-6}

C_{16} 5.0284×10^{-7} C_{17} 2.3906×10^{-8} C_{19} 7.1030×10^{-8}

C_{21} 2.8323×10^{-8}

Three-dimensional surface(2)

C_5 -3.7101×10^{-3} C_7 -4.1036×10^{-3} C_8 4.2896×10^{-6}

C_{10} -8.4314×10^{-6} C_{12} -8.1477×10^{-8} C_{14} 1.1846×10^{-6}

C_{16} 2.8608×10^{-7} C_{17} 8.8332×10^{-9} C_{19} 3.2284×10^{-8}

C_{21} 1.2745×10^{-8}

Three-dimensional surface(3)

C_5 1.5613×10^{-2} C_7 1.5901×10^{-2} C_8 3.8223×10^{-4}

C_{10} -5.9546×10^{-5} C_{12} -5.8106×10^{-5} C_{14} -4.2859×10^{-5}

C_{16} -2.2163×10^{-5} C_{17} 1.1940×10^{-6} C_{19} 2.0760×10^{-6}

C_{21} 1.0626×10^{-6}

Example 1 4

Surface No.	Radius of curvature	Surface separation	Refractive index	Abbe's No.
			(Displacement)	(Tilt angle)
1	∞(Pupil)			

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2	Three-dimensional surface(1)		1.5163	64.15
(1ST SF)		Y -10.123	θ	20.33°
		Z 43.489		
3	Three-dimensional surface(2)		1.5163	64.15
(2ND SF)		Y 1.103	θ	-10.31°
(REFL)		Z 65.000		
4	Three-dimensional surface(1)	Y -10.123	θ	20.33°
(1ST SF)		Z 43.489		
5	∞	Y 17.608	θ	-13.99°
(Image display plane)		Z 30.846		

Three-dimensional surface(1)

C_5 1.0401×10^{-2}	C_7 8.6572×10^{-3}	C_8 9.8267×10^{-5}
C_{10} 2.0456×10^{-4}	C_{12} -9.4226×10^{-6}	C_{14} 1.6262×10^{-6}
C_{16} 4.0506×10^{-6}	C_{17} 3.2669×10^{-7}	C_{19} 2.1072×10^{-7}
C_{21} 1.5355×10^{-7}		

Three-dimensional surface(2)

C_5 -2.5798×10^{-3}	C_7 -3.0708×10^{-3}	C_8 -3.2024×10^{-5}
C_{10} -3.3909×10^{-6}	C_{12} 2.9430×10^{-6}	C_{14} 4.3427×10^{-6}
C_{16} 3.4981×10^{-6}	C_{17} -2.8763×10^{-8}	C_{19} 4.0895×10^{-8}
C_{21} 5.4666×10^{-8}		

Example 1 7

Surface No.	Radius of curvature	Surface separation	Refractive index	Abbe's No.
			(Displacement)	(Tilt angle)
1	∞(Pupil)			
2	Three-dimensional surface(1)		1.5000	55.55
(1ST SF)			Y 18.958	θ 7.69°

				Z	30.730		
3	Three-dimensional surface(2)		1.5000				55.55
(2ND SF)				Y	9.165	θ	-13.84°
(REFL)				Z	48.107		
4	Three-dimensional surface(1)		1.5000				55.55
(1ST SF)				Y	18.958	θ	7.69°
(REFL)				Z	30.730		
5	Three-dimensional surface(2)		1.5000				55.55
(2ND SF)				Y	9.165	θ	-13.84°
(REFL)				Z	48.107		
6	Three-dimensional surface(3)		1.5000				55.55
(4TH SF)				Y	34.128	θ	-31.50°
				Z	30.758		
7	∞			Y	47.350	θ	-34.92°
(Image display plane)				Z	35.893		

Three-dimensional surface(1)

C_5	-4.9463×10^{-3}	C_7	-3.4912×10^{-3}	C_8	6.9477×10^{-5}
C_{10}	1.7114×10^{-4}	C_{12}	1.0830×10^{-6}	C_{14}	-2.2541×10^{-7}
C_{16}	4.5743×10^{-6}	C_{17}	6.1581×10^{-8}	C_{19}	4.7667×10^{-8}
C_{21}	-1.9359×10^{-7}	C_{23}	-1.3103×10^{-10}	C_{25}	-7.7572×10^{-10}
C_{27}	7.0783×10^{-10}	C_{29}	5.3774×10^{-9}	C_{30}	4.7726×10^{-12}
C_{32}	1.3699×10^{-11}	C_{34}	7.4217×10^{-11}	C_{36}	-1.3460×10^{-10}

Three-dimensional surface(2)

C_5	-5.9243×10^{-3}	C_7	-5.4509×10^{-3}	C_8	3.4016×10^{-5}
C_{10}	7.9633×10^{-5}	C_{12}	-4.1470×10^{-7}	C_{14}	1.0233×10^{-6}
C_{16}	2.6471×10^{-6}	C_{17}	2.3016×10^{-9}	C_{19}	3.3134×10^{-8}
C_{21}	-1.6456×10^{-8}	C_{23}	-1.3255×10^{-10}	C_{25}	-4.9215×10^{-10}
C_{27}	-3.3070×10^{-10}	C_{29}	4.1802×10^{-9}		

Three-dimensional surface(3)

C$_5$ 7.9798×10^{-3} C$_7$ 1.7546×10^{-2} C$_8$ -1.1020×10^{-4}

C$_{10}$ 9.4392×10^{-4} C$_{12}$ -3.9282×10^{-6} C$_{14}$ -7.3326×10^{-6}

C$_{16}$ -1.4273×10^{-5}

（1） $\theta_{r3} = 46.48°$

Although in the above-described examples the optical systems are constructed by using aspherical surfaces, anamorphic surfaces and three-dimensional surfaces defined by the above equations (a), (b) and (c), it is also possible to use surface configurations expressed by Zernike polynomials as defined by the following equation (d) and three-dimensional surfaces symmetric with respect to the X-axis direction as defined by the following equation (e). That is, curved surfaces expressed by any defining equations can be used.

Plane-symmetry three-dimensional surfaces may also be defined by Zernike polynomials. That is, the configuration of a plane-symmetry three-dimensional surface may be defined by the following equation (d). The Z-axis of the defining equation (d) is the axis of Zernike polynomial.

$$X = R \times \cos(A)$$

$$Y = R \times \sin(A)$$

$$
\begin{aligned}
Z = D_2 \\
&+ D_3 R \cos(A) + D_4 R \sin(A) \\
&+ D_5 R^2 \cos(2A) + D_6 (R^2 - 1) + D_7 R^2 \sin(2A) \\
&+ D_8 R^3 \cos(3A) + D_9 (3R^3 - 2R) \cos(A) \\
&+ D_{10} (3R^3 - 2R) \sin(A) + D_{11} R^3 \sin(3A) \\
&+ D_{12} R^4 \cos(4A) + D_{13} (4R^4 - 3R^2) \cos(2A) \\
&+ D_{14} (6R^4 - 6R^2 + 1) + D_{15} (4R^4 - 3R^2) \sin(2A) \\
&+ D_{16} R^4 \sin(4A) + D_{17} R^5 \cos(5A) \\
&+ D_{18} (5R^5 - 4R^3) \cos(3A) \\
&+ D_{19} (10R^5 - 12R^3 + 3R) \cos(A) \\
&+ D_{20} (10R^5 - 12R^3 + 3R) \sin(A)
\end{aligned}
$$

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$$+D_{21}(5R^5-4R^3)\sin(3A)+D_{22}R^5\sin(5A)$$
$$+D_{23}R^6\cos(6A)+D_{24}(6R^6-5R^4)\cos(4A)$$
$$+D_{25}(15R^6-20R^4+6R^2)\cos(2A)$$
$$+D_{26}(20R^6-30R^4+12R^2-1)$$
$$+D_{27}(15R^6-20R^4+6R^2)\sin(2A)$$
$$+D_{28}(6R^6-5R^4)\sin(4A)+D_{29}R^6\sin(6A)\ldots\ldots$$

$$\ldots(d)$$

It should be noted that the plane-symmetry three-dimensional surface in the above equation is expressed as a surface which is symmetric with respect to the X-axis direction. In the above equation, D_m (m is an integer of 2 or higher) are coefficients.

A three-dimensional surface symmetric with respect to the X-axis direction may be defined in correspondence to the above equation (c) as follows:

$$Z=C_2$$
$$+C_3Y+C_4|X|$$
$$+C_5Y^2+C_6Y|X|+C_7X^2$$
$$+C_8Y^3+C_9Y^2|X|+C_{10}YX^2+C_{11}|X^3|$$
$$+C_{12}Y^4+C_{13}Y^3|X|+C_{14}Y^2X^2+C_{15}Y|X^3|+C_{16}X^4$$
$$+C_{17}Y^5+C_{18}Y^4|X|+C_{19}Y^3X^2+C_{20}Y^2|X^3|$$
$$+C_{21}YX^4+C_{22}|X^5|$$
$$+C_{23}Y^6+C_{24}Y^5|X|+C_{25}Y^4X^2+C_{26}Y^3|X^3|$$
$$+C_{27}Y^2X^4+C_{28}Y|X^5|+C_{29}X^6$$
$$+C_{30}Y^7+C_{31}Y^6|X|+C_{32}Y^5X^2+C_{33}Y^4|X^3|$$
$$+C_{34}Y^3X^4+C_{35}Y^2|X^5|+C_{36}YX^6+C_{37}|X^7|$$

$$\ldots(e)$$

Incidentally, it is possible to construct an image

display apparatus for a single eye by preparing a combination of an ocular optical system arranged as described above and an image display device. Alternatively, it is possible to construct an image display apparatus for

5   both eyes by preparing a pair of combinations of an ocular optical system arranged as described above and an image display device for the left and right eyes, and supporting them apart from each other by the interpupillary distance, i.e. the distance between the two eyes. In this way, it is

10   possible to form a stationary or portable image display apparatus which enables the observer to see with a single eye or both eyes.

Fig. 21 shows an image display apparatus designed for a single eye (in this case, the apparatus is designed for the

15   left eye), and Fig. 22 shows an image display apparatus designed for both eyes. In Figs. 21 and 22, reference numeral 31 denotes a display apparatus body unit. In the case of Fig. 21, the display apparatus body unit 31 is supported by a support member through the observer's head

20   such that the display apparatus body unit 31 is held in front of the observer's left eye. In the case of Fig. 22, the display apparatus body unit 31 is supported by a support member through the observer's head such that the display apparatus body unit 31 is held in front of both the

25   observer's eyes. The support member has a pair of left and right front frames 32 each joined at one end thereof to the display apparatus body unit 31. The left and right front frames 32 extend from the observer's temples to the upper

portions of his/her ears, respectively. A pair of left and right rear frames 33 are joined to the other ends of the left and right front frames 32, respectively, and extend over the left and right side portions of the observer's

5   head. In the case of Fig. 22, the support member further has a top frame 34 joined at both ends thereof to the other ends of the left and right rear frames 33, respectively, such that the top frame 34 supports the top of the observer's head.

10   A rear plate 35 is joined to one front frame 32 near the joint to the rear frame 33. The rear plate 35 is formed from an elastic member, e.g. a metal leaf spring. In the case of Fig. 22, a rear cover 36, which constitutes a part of the support member, is joined to the rear plate 35 such

15   that the rear cover 36 can support the apparatus at a position behind the observer's ear in a region extending from the back part of the head to the base of the neck. A speaker 39 is mounted inside the rear plate 35 or the rear cover 36 at a position corresponding to the observer's ear.

20   A cable 41 for transmitting external image and sound signals is led out from the display apparatus body unit 31. In the case of Fig. 22, the cable 41 extends through the top frame 34, the rear frames 33, the front frames 32 and the rear plate 35 and projects to the outside from the rear end

25   of the rear cover 36. In the case of Fig. 21, the cable 41 projects from the rear end of the rear plate 35. The cable 41 is connected to a video reproducing unit 40. It should be noted that reference numeral 40a denotes a switch and

volume control part of the video reproducing unit 40.

The cable 41 may have a jack and plug arrangement attached to the distal end thereof so that the cable 41 can be detachably connected to an existing video deck. The

5   cable 41 may also be connected to a TV signal receiving tuner so as to enable the user to enjoy watching TV. Alternatively, the cable 41 may be connected to a computer to receive computer graphic images or message images or the like from the computer. To eliminate the bothersome cord,

10   the image display apparatus may be arranged to receive external radio signals through an antenna connected thereto.

Further, the ocular optical system of the image display apparatus according to the present invention can be used as an image-forming optical system. For example, as shown in

15   Fig. 23, the ocular optical system may be used in a finder optical system F_i of a compact camera C_a in which a photographic optical system O_b and the finder optical system F_i are provided separately in parallel to each other. Fig. 24 shows the arrangement of an optical system in a case

20   where the ocular optical system according to the present invention is used as such an image-forming optical system. As illustrated, the ocular optical system DS according to the present invention is disposed behind a front lens group GF and an aperture diaphragm D, thereby constituting an

25   objective optical system L_t. An image that is formed by the objective optical system L_t is erected by a Porro prism P, in which there are four reflections, provided at the observer side of the objective optical system L_t, thereby

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enabling an erect image to be observed through an ocular lens O_c.

Although the prism optical element, image observation apparatus and image display apparatus according to the
5   present invention have been described above by way of some examples, it should be noted that the present invention is not necessarily limited to these examples, and that various modifications may be imparted thereto without departing from the scope of the present invention.
10   As will be clear from the foregoing description, the present invention makes it possible to provide an image display apparatus usable as an image observation apparatus which has an extremely thin and compact ocular optical system and yet suffers from minimal unwanted light and
15   provides an observation image that is clear even at a wide observation field angle.

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